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GCA Corp, Bedford, Mass GCA Technology Div

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IMPROVEMENTS TO SINGLE-SOURCE MODEL
VOLUME 3: FURTHER ANALYSIS OF MODELING RESULTS

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Turbulent Diffusion		Point Sources	
Mathematical Models		Model Validation	
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ABSTRACT

This report documents an evaluation of the model performance stratified by six stability classes, three wind speed classes, and three mixing height classes. The model accuracy is found to be dependent on stability class. For stabilities A and B, the model shows some tendency to overestimate concentrations, especially near the plant. For stabilities D, E, and F, the model greatly underestimates concentrations at all but the most distant sampler. For stability C, the model tends to agree with the measurements. Higher wind speeds result in a trend toward overestimates at the Muskingum plant, and a trend toward underestimates at the Canal plant. Fot the Canal plant, there does not appear to be a definite pattern between the accuracy of the model estimates and mixing height. However, at the Muskingum plant, large underestimates occur for the lowest mixing height class. This implies that the model is treating the plume as penetrating the top of the mixed layer (with resulting concentration estimates of zero) more frequently than actually happens.

CONTENTS

Page

Abstract iii

List of Figures vi

List of Tables vii

Project Summary viii

Sections

I Introduction 1

II Site and Data Base Description 4

III Model Validation Procedures 13

IV Model Validation Results 16

V Conclusions and Recommendations 22

VI References 24

Appendix

A Cumulative Frequency Distributions 25

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LIST OF FIGURES

No.		Page
1	Map of Eastern Massachusetts and Rhode Island Showing Locations of the Canal Plant	5
2	Sketch of the Canal Plant Area Showing the Locations of the Four Automatic SO_2 Stations by the Symbol ⊙	8
3	Sketch of the Muskingum Plant Areas Showing Locations of Four Automatic SO_2 Monitoring Stations	11
4	Determination of Hourly Mixing Heights	17

LIST OF TABLES

No.		Page
1	Plant Characteristics	6
2	Monthly Percent Sulfur Content of Fuel	7
3	Sulfur Dioxide Monitoring Stations for the Canal and Muskingum Plants	9
4a	Percentile for Wind Speed (Adjusted to 7 meters) and Mixing Height Stratification	15
4b	Percent Occurence of Different Stabilities for Canal and Muskingum	15
5	Stability Class as a Function of Net Radiation and Wind Speed	18
6	Model Validation Results for all Plants, Receptors and Meteorological Conditions (O - Overprediction, U = Underprediction, A = Agreement)	21

PROJECT SUMMARY

This is a summary of the results and conclusions made in the three parts of this study, with some relevant interpretive comments.

The first part of the study deals with analyses of ratios of peak 1-hour to mean 3-hour, and peak 1-hour to mean 24-hour concentrations. Some work had been done in previous studies; however, those results seemed to be biased by the presence of a large number of very low concentrations. In the present study this problem is avoided by analyzing only the peak-to-mean ratios whose peak 1-hour value exceeds some arbitrary threshold concentration. Actually three such threshold concentrations are selected, corresponding to the 95th, 98th and 99th percentile values of the 1-hour concentration distribution. The use of this restricted data set results in more nearly log-normal frequency distributions of peak-to-mean ratios, and lower standard geometric deviations of the peak-to-mean ratios. The geometric means and the medians increase slightly. A comparison of the 50th and 95th percentile values of the peak 1-hour to mean 3-hour, and peak 1-hour to mean 24-hour ratios is shown in Table S-1 below, for both the complete data set (from earlier studies) and the restricted data set (the present study). The results of a TVA study at the Paradise power plant in Kentucky are also included for comparison.

Conservative estimates of maximum 24-hour concentrations have often been calculated by dividing the estimated maximum 1-hour value by a factor of four. This factor was originally chosen from the 95th percentile ratio found around the Paradise plant (see Table S-1). The peak 1-hour to peak 24-hour ratio (over a year's time) should occur somewhere between the 50th percentile and the 95th percentile values. The value (assuming the

same approximate degree of conservatism) is generally supported by the peak-to-mean ratio distribution of the restricted data set (Table S-1).

The second part of the study involves testing and evaluation of several possible model improvements. Specifically, the following cases are tested for the Canal power plant and the Muskingum River power plant:

1. Base Case--Pasquill-Turner stability assignments with Pasquill-Turner dispersion curves;
2. Pasquill-Turner stability assignments with Gifford-Briggs dispersion curves;
3. Smith-Singer stability assignments with Smith-Singer dispersion curves (one plant only);
4. Pasquill-Turner stability assignments with F.B. Smith σ_z curves and Pasquill-Turner σ_y curves;
5. F.B. Smith fractional stability assignments with F.B. Smith σ_z curves and Pasquill-Turner σ_y curves;
6. Base case stability assignments and dispersion curves, but with buoyancy flux (for plume rise calculations) made proportional to emission rate.

The net outcome is that the proposed changes yield neither significantly better nor significantly worse results than the base case.

Based upon the results of this study it is recommended that the methods currently used for the calculation of dispersion coefficients and the selection of stability classes not be replaced by alternate techniques, at least until further model validation studies are conducted. Since data from only two power plants are used in this study the results should not be considered definitive. Nevertheless, even from these limited results, a number of conclusions can be drawn:

1. The similarity between the Pasquill-Turner and Gifford-Briggs dispersion coefficients (except for stability A) requires that a large number of model validation exercises be carried out to determine which method is more accurate.

2. The use of the Smith-Singer stability assignment and dispersion calculation methods in the Single Source Model may yield unrealistic frequency distributions of 1-hour concentrations. This observation must be qualified, however, by the fact that the validation is carried out only for the Muskingum plant. Since the rather subjective stability assignment scheme may have been carried out differently at the Muskingum plant, the use of the Smith-Singer dispersion coefficients with the Single Source Model may give better agreement with measured concentrations if applied elsewhere.

3. Due to the strong variation of calculated concentrations as a function of stability, the use of fractional stability assignments should, in principle, lead to more accurate model predictions. The F.B. Smith stability classification method does not, however, provide better agreement between measured and calculated concentration frequency distributions, primarily because of its tendency to select slightly more unstable conditions.

4. The use of a variable buoyancy flux in the Single Source Model does little to improve the agreement between measured and calculated concentration frequency distributions. This conclusion is similar to others reached when more detailed or applicable emissions or meteorological data have been used in model validation exercises. The success or failure of the model in any given application is much more a function of the assumptions regarding plume rise, dispersion, and terrain effects that form the theoretical basis for the model.

The third part of the study consists of an evaluation of the model performance stratified by six stability classes, three wind speed classes and three mixing height classes.

The model accuracy is found to be dependent on stability class. For stabilities A and B, the model shows some tendency to over estimate concentrations, especially near the plant. This indicates that vertical dispersion is overestimated in the model, and σ_z values are too large.

For stabilities D, E, and F, the model greatly underestimates concentrations at all but the most distant sampler. This indicates that vertical dispersion in the model is underestimated for these stabilities. For stability C, the model tends to agree with the measurements.

Higher wind speeds result in a trend toward overestimates at the Muskingum plant, and a trend toward underestimates at the Canal plant.

For the Canal plant, there does not appear to be a definite pattern between the accuracy of the model estimates and mixing height. However, at the Muskingum plant, large underestimates occur for the lowest mixing height class. This implies that the model is treating the plume as penetrating the top of the mixed layer (with resulting concentration estimates of zero) more frequently than actually happens. Thus, either the mixing heights are underestimated, or the concept of complete plume penetration may be in error.

Table S-1. COMPARISON OF PEAK-TO-MEAN RATIOS FOR COMPLETE AND RESTRICTED DATA SETS

		Complete data set		Restricted data set[a]	
Plant name	Averaging times of ratios	50th percentile of ratios[b]	95th percentile of ratios[b]	50th percentile of ratios[b]	95th percentile of ratios[b,e]
Canal	1-3 hour[c]	1.50	1.02	1.89	~1.20
	1-24 hour[d]	5.37	1.69	8.25	~3.8
Stuart	1-3 hour	1.55	1.00	1.58	~1.00
	1-24 hour	5.95	1.93	7.70	~2.7
Muskingum	1-3 hour	1.74	1.00	1.73	~1.15
	1-24 hour	6.65	2.38	6.90	~3.7
Philo	1-3 hour	1.77	1.04	1.89	~1.20
	1.24 hour	6.98	2.47	7.79	~3.8
Paradise	1-3 hour	1.63	1.00	--	--
	1-24 hour	12.4	4.00	--	--

[a] Restricted to peak-to-mean ratios whose peak values exceed the value of the 99th percentile of the 1 hour concentrations.

[b] Percentile values given in terms of cumulative percent of ratios greater than the given values.

[c] Peak 1-hour to average 3-hour ratio for measured minus background SO_2 concentration.

[d] Peak 1-hour to average 24-hour ratio for measured minus background SO_2 concentration.

[e] These values were estimated from the appropriate figures in Volume 1 of this series.

SECTION I

INTRODUCTION

This is the third in a series of reports dealing with possible improvements to the EPA Single Source Model. The evaluation of these model improvements is based upon earlier model validation studies for four fossil-fueled power plants.[1,2] The first volume of this series examined in detailed the peak to mean concentration ratio distributions (1- to 3 hour and 1- to 24 hour) constructed by use of hourly SO_2 measurements taken in the vicinity of the four plants. The main objective of this study was to investigate the properties of these peak to mean frequency distributions as the 3 or 24-hour periods with peak 1-hour concentrations below various threshold values were excluded. The purpose of this exercise was to develop representative peak to mean concentration ratios which could be used to extrapolate model predictions of peak 1-hour concentrations to peak 3-hour and 24-hour values. During the second phase of our study we compared different sets of dispersion curves (Pasquill-Turner, Gifford-Briggs, F.B. Smith and Smith-Singer) and stability assignment methods (F.B. Smith and Smith-Singer) with respect to their ability to yield accurate predictions of 1-hour SO_2 concentration frequency distributions at two of the power plants used in earlier studies. The basic conclusion reached during this phase of the study was that the Single Source Model, as it now stands gives the best agreement with measured concentrations. This result must be qualified by the fact that only two plants were used and that not all model formulations were tested. Even after the second phase of the study was completed there still remained the question whether the Single Source Model was providing reasonable estimates of ground level concentrations on an hour by hour basis. Up to this point, all of our model validation studies had been based upon a comparison of cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background. In principle one should be able to make hour by hour comparisons of predicted and measured concentrations, but in practice even a local wind direction measurement is not a reliable indicator of the plume trajectory. One can, however, carry out a more detailed model evaluation by comparing observed and calculated frequency distributions of concentrations for specific types of meteorological conditions. Of special interest is the comparison of observed and calculated distributions for the different atmospheric stability classes.

For a test of this stratified comparison of measured and calculated concentration frequency distributions we chose the Canal Power Plant in Massachusetts and the Muskingum Power Plant in Ohio. Results of an earlier Single Source Model validation study at the Canal Plant[1] showed an underprediction at all four receptor locations. Through a comparison of model predictions with measured concentrations for each stability we hoped to gain a better understanding for the reasons for the underprediction at Canal. Also this procedure would help determine whether the relatively good model agreement obtained for 1-hour concentrations at the Muskingum plant was physically reasonable or simply due to a fortuitous combination of over and underpredictions. In addition to developing comparisons of measured and calculated concentration frequency distributions for each stability, we have also stratified the comparison according to selected wind speed and mixing height ranges. The comparison by wind speed could point out difficulties with the plume rise formulation or the inadequate treatment of terrain effects. The model validation by mixing height range should reveal, especially for the lower range of mixing heights, any problems with the way inversion penetration or plume reflection is currently handled in the model.

In the next section we shall describe the data base used in the stratified comparison of measured and calculated concentration frequency distributions.

Section III will deal with the techniques used in the stratification of measurements and Single Source Model predictions according to stability, wind speed and mixing height. Results of the validation study will be presented in Section IV followed by a summary and conclusions in Section V.

SECTION II

SITE AND DATA BASE DESCRIPTION

In this section we shall describe the site characteristics, SO_2 monitoring program and meteorological data base for the two power plants (Canal and Muskingum) included in the detailed model validation study. Each topic will be covered on a plant-by-plant basis. Although this site and data base description has been presented in previous model validation reports[1,2], it is repeated here to provide a quick reference for physical site parameters such as source-receptor distance, which are needed for the analysis of the model prediction for different ranges of meteorological parameters.

CANAL PLANT

Site Description

The Canal Plant is located on the south side of the Cape Cod Canal about 1.6 kilometers from the entrance on Cape Cod Bay (Figure 1). The surrounding terrain is gently rolling with elevations generally less than 60 meters above mean sea level. The highest elevations in the area are about 90 meters above sea level in the western end of the Cape. Most of the area is covered with scrub pine forests and low vegetation.

Data for the study were collected in 1971. During that year, the plant consisted of a single oil-fired unit with a generating capacity of 560 megawatts. The top of the stack was about 91 meters above grade and 5.6 meters in diameter. The main power plant structure to the north of the stack totally enclosed the turbine generator and boiler. The roofs of the turbine and boiler rooms were about 30 meters and 59 meters above grade

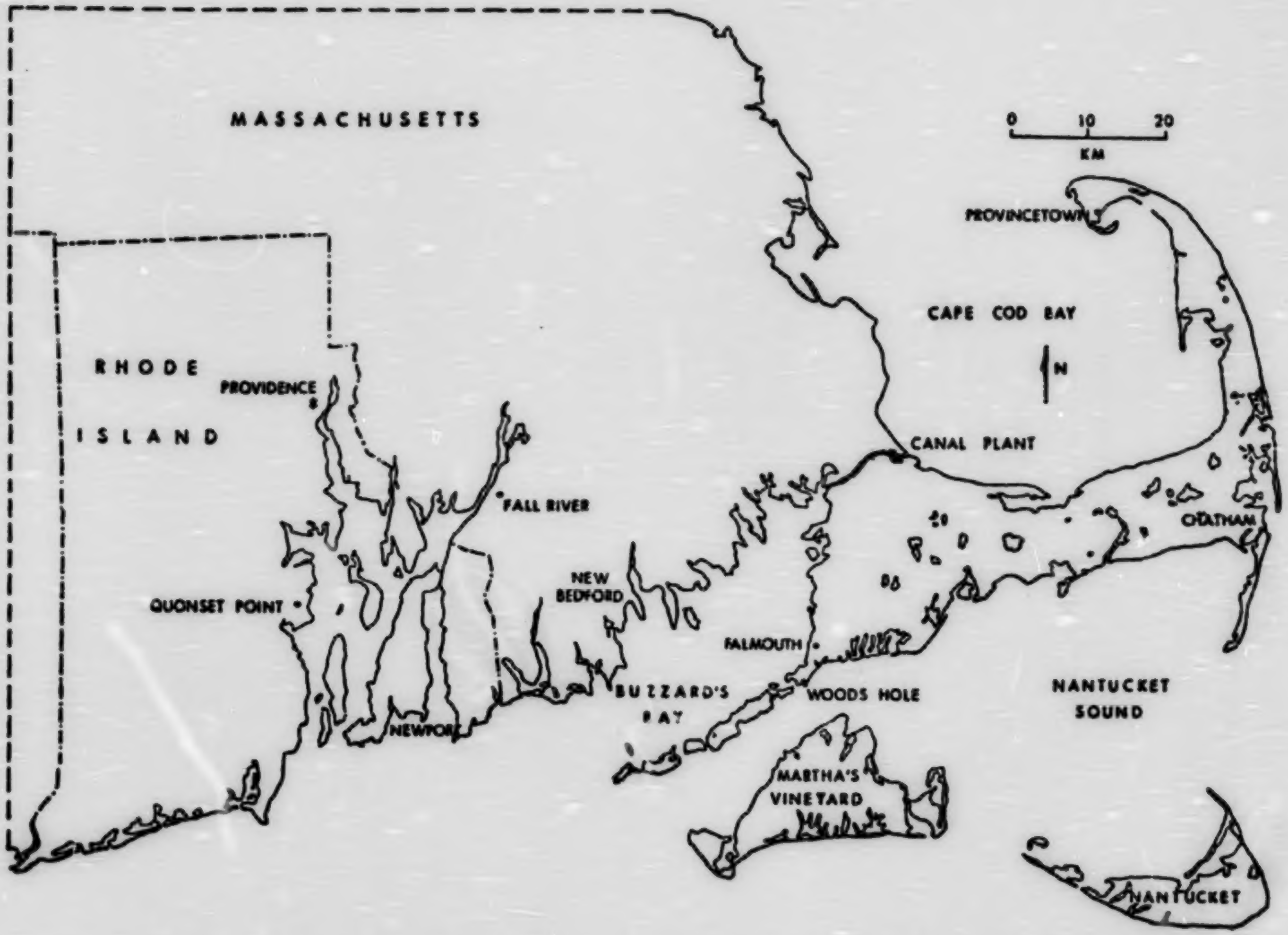
MASSACHUSETTS
RHODE ISLAND
PROVIDENCE
QUONSET POINT
FALL RIVER
NEWPORT
NEW BEDFORD
BUZZARD'S BAY
FALMOUTH
WOODS HOLE
CANAL PLANT
CAPE COD BAY
N
PROVINCETOWN
CHATHAM
NANTUCKET SOUND
MARTHA'S VINEYARD
NANTUCKET
0 10 20
KM

Figure 1. Map of eastern Massachusetts and Rhode Island showing locations of the Canal Plant. Meteorological observations were used from Quonset Point Naval Air Station and Chatham

respectively. Stack and boiler data are given in Table 1. The 1971 monthly percent sulfur content of the fuel used at the Canal Plant is given in Table 2.

Table 1. PLANT CHARACTERISTICS

	Plant		
	Canal	Muskingum	
Characteristic	Stack 1	Stack 1	Stack 2
Stack height, m	91	251	251
Diameter, m	5.6	7.6	6.7
Velocity, m/sec	-	28.5	24.8
Temperature, °F	-	430	425
Number of boilers per stack	1	4	1
Maximum generating capacity per stack, MW	560	876	591
Average per stack, MW	-	748	487
Plant total, MW	560	1467	
Plant average, MW	-	1235	

Table 2. MONTHLY PERCENT SULFUR CONTENT OF FUEL

Month	Canal	Muskingum
January	2.0	4.9
February	1.9	4.8
March	2.1	4.8
April	1.9	4.5
May	2.1	4.7
June	2.1	5.0
July	2.1	4.7
August	2.0	4.7
September	1.9	4.3
October	0.9	4.6
November	1.0	4.5
December	0.9	4.4

Overview of Canal Plant Monitoring Program

SO_2 concentrations are measured at four locations on a continous basis with Ultragas SO_2 Analyzers manufactured in Germany by H. Wosthoff. These instruments measure sulfur dioxide by the increase in conductivity of an acidified hydrogen peroxide solution and have a full scale reading of 0.4 ppm. The instruments do not conform to the reference method for sulfur dioxide or to any of the specified equivalent methods. They have, however, been extensively studied and one comparison noted a correlation coefficient of 0.99 with the West-Gaeke method. The instruments used provide a continuous real-time chart trace and a tape printout giving data, time, and average concentration over consecutive 30 minutes. The sensitivity of the instrument in combination with the chart recorder is approximately 0.005 ppm. The locations of the SO_2 monitors with respect to the Canal Plant are given in Figure 2 and Table 3.

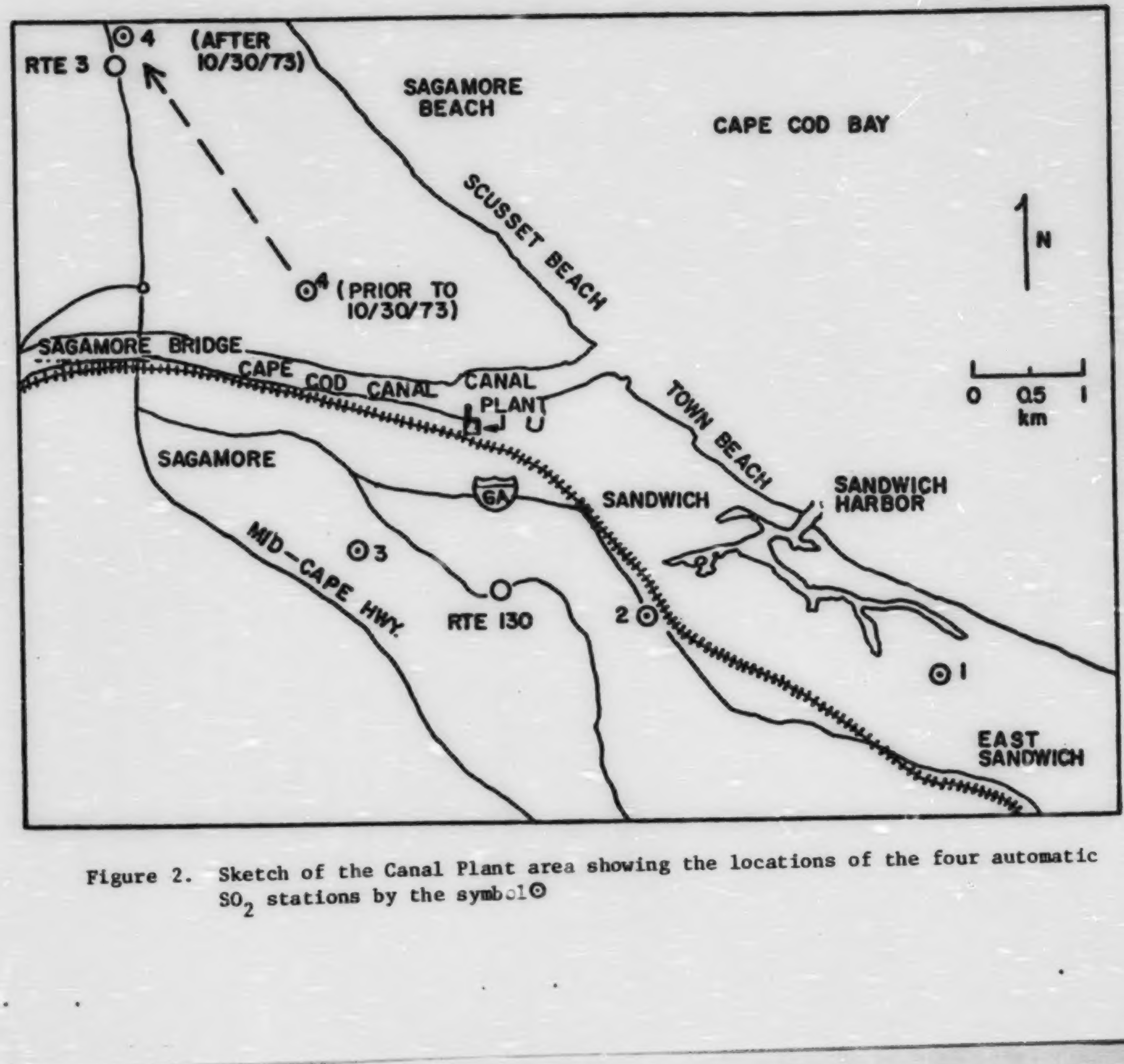
RTE 3
4
(AFTER 10/30/73)
SAGAMORE BEACH
CAPE COD BAY
SCUSSET BEACH
N
4 (PRIOR TO 10/30/73)
SAGAMORE BRIDGE
CAPE COD CANAL
CANAL PLANT
0
0.5
1
km
TOWN BEACH
SAGAMORE
6A
SANDWICH
SANDWICH HARBOR
3
MID-CAPE HWY.
RTE 130
2
1
EAST SANDWICH

Figure 2. Sketch of the Canal Plant area showing the locations of the four automatic SO_2 stations by the symbol ⊙

Table 3. SULFUR DIOXIDE MONITORING STATIONS FOR THE CANAL AND MUSKINGUM PLANTS

Plant	Station		Distance, km	Heading, degrees	Elevation above stack base, m
	No.	Name			
Canal	1		4.7	119	10
	2		2.3	138	4
	3		1.4	224	40
	4		2.0	312	20
Muskingum	1	Beverly	5.3	140	64
	2	Hackney	4.3	40	82
	3	Rich Valley	8.3	35	101
	4	Caldwell	19.6	35	128
	-	Top of stacks	-	-	251

Meteorological Data for Canal Plant

Bendix-Friez Aerovanes are used to provide local wind speed and direction data. Through July 1971, the principal source of wind data was the Aerovane mounted on a 12.2 meter mast located on the 58.8 meter boiler-room roof. Since July 1971, wind data are obtained from a second Aerovane installed on a 44 meter tower near the top of Telegraph Hill approximately 5 kilometers south-southwest of the Canal Plant. This hourly wind data was used to define upwind receptor locations for calculation of hourly background concentrations. A station was considered to be a background receptor if it was located outside the boundaries of a 90 degree sector centered about the wind flow vector. The concentrations for these background stations were then averaged and subtracted from the hourly concentrations at all stations. Any resultant negative concentrations were set equal to zero. The on-site wind speed, wind direction and ambient temperature data were also input to the Single Source Model after proper conversion to a wind measurement height of 7 meters. These stability dependent wind speed corrections were based upon hourly atmospheric stabilities derived from a Single Source Model Preprocessor run using surface meteorological data for 1971 collected at Quonset Point Naval Air Station. Hourly mixing heights for 1971 were based upon surface data from Quonset Point, Rhode Island and upper air observations taken at Chatham, Massachusetts. In this way a "hybrid" Preprocessor output file was generated containing on-site wind speed, wind direction and temperature measurements and nonlocal stability and mixing height assignments.

MUSKINGUM PLANT

Site Description

The Muskingum Plant is located in southeastern Ohio on the Muskingum River about 6 kilometers northwest of the town of Beverly. Figure 3 indicates the location of the plant, the SO_2 monitoring sites, and the surrounding towns. The plant is in the river valley about 500 meters from the valley walls which rise about 75 meters above the valley floor. The two 251 meter stacks are 640 meters apart and extend about 185 meters above the surrounding terrain. During 1973 the plant consisted of five coal-fired units with a total capacity of 1467 megawatts (Table 1). Percent sulfur content of the fuel for 1973 is given in Table 2.

Overview of the Muskingum Monitoring Program

Four sulfur dioxide monitoring stations make up the monitoring network (Figure 3 and Table 3). Data were available from all stations for January 1 to November 21, 1973. During the entire year of 1973, Station 1 missed 57 days and the other three stations missed approximately 41 days. Instruments at Muskingum were Leeds & Northrup Company, Catalog No. 7860-SW, Aeroscan Air Quality Monitors. The sample was obtained by passing ambient air taken from 5 feet above ground level, through an absorption column along with an absorption solution. The sample analysis method was by electrolytic conductivity. Data were taken continuously and listed every hour. Each instrument was automatically zeroed once a day.

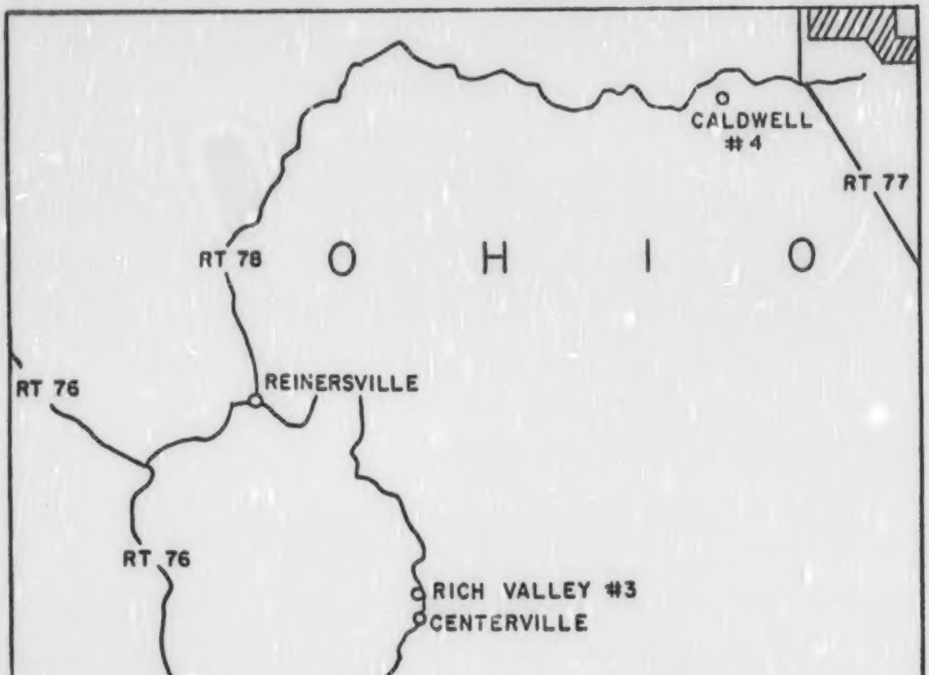
CALDWELL
#4
RT 77
RT 78
OHIO
RT 76
REINERSVILLE
RT 76
RICH VALLEY #3
CENTERVILLE
HACKNEY #2
N
RT 76
MUSKINGUM PLANT
STACK 1
STACK 2
KILOMETERS
0 1 2 3 4 5
RT 77
MUSKINGUM R
BEVERLY
#1
RT 77
RT 76

Figure 3. Sketch of the Muskingum Plant area showing locations of four automatic SO_2 monitoring stations

The manufacturer's performance accuracy specifications for this instrument are as follows. In a typical ambient atmosphere which includes the normal interfering gases, this instrument has:

- Zero drift = 2 percent of full scale per week
- Sensitivity drift $<$ 1 percent of full scale per week
- Reproductibility $<$ 1 percent of full scale
- Sensitivity = 0.01 ppm
- Recorder error $<$ 0.5 percent of full scale
- Range = approximately 0 to 1 ppm

Meteorological Data for Muskingum Plant

There were two wind monitoring stations at the Muskingum Plant consisting of Bendix-Friez Aerovane wind speed and direction devices. One station was located 24 meters above ground at Beverly, and the other at the Hackney SO_2 monitoring station, where the wind monitors were also located 24 meters above ground. The data from Hackney was used in this study, as it was higher and common to more stations, but Beverly data was used when the Hackney system was not recording. On-site hourly wind direction data was used for the assignment of upwind receptor locations whose concentrations were then used in a background subtration procedure identical to the one described for the Canal plant. Wind speeds at these two meteorological stations were converted to the 7 meter height by means of the stability dependent power law currently used in the Single Source Model and hourly stabilities based upon Huntington, West Virginia surface observations for 1973. A hybrid Preprocessor output file was then constructed using local wind direction and corrected wind speed data in conjunction with ambient temperature and stability assignments from Huntington. Hourly mixing heights were based upon surface and upper air data both collected at Huntington.

SECTION III

MODEL VALIDATION PROCEDURES

As was pointed out in Section II, local meteoroligical data was used for model input in the Canal and Muskingum validation studies. Unfortunately observations of ceiling height and percent cloud cover were not obtained on site but had to be taken from observations made at stations over a 100 kilometers distant. Wind speeds measured on site could not be used in conjunction with off site ceiling height and percent cloud cover observations to calculate the atmospheric stability index since the on site wind speeds were measured on towers higher than the standard 7 meter height used in the Pasquill-Turner stability assignment scheme. The on site wind speed was still used in the calculations of plume rise and plume dilution after they were converted to stack top wind speeds by means of a stability dependent power law profile. On site wind directions were used both for model calculations and background subtraction. It should be noted that hourly wind direction inputs to the model are only specified to the nearest 10 degrees. The model chooses the location of the plume axis within the 10 degree interval by means of a random number routine. For the Canal Plant validation, on site temperature measurements were used.

Since the Single Source Model was described in Volume II[3] of this series, we will deal briefly with those aspects of the model most pertinent to the present model validation study. The basis for the selection of wind speed and mixing height intervals for the Canal and Muskingum plants was an analysis of the Meteorological Preprocessor Program output for each of these facilities. Input to this program consists of wind speed (knots), wind direction sector (1 to 36), temperature (°F), total cloud cover (tenths), ceiling (hundreds of feet), and twice daily mixing heights (meters). The output file contains hourly values of stability index, mixing height(meters), temperature (^{o}K), windspeed (meters/sec), flow vector (wind direction plus 180 degrees), and randomized flow vector. The randomized flow vector is equal to the flow vector minus 4 degrees plus a random number between 0 and 9 degrees. The procedure for the determination of hourly "rural" mixing heights from the twice daily mixing height measurements is decribed in Volume II[3]. Hourly stabilities are specified according to the system given by Turner[4] employing Pasquill's classification scheme with the addition of a stability class 7 (i.e., G) for which the assumption is made that the plume does not reach the ground. Pasquill-Turner dispersion curves[5] for stabilities A through F are used in the calculation of ground level concentrations. Plume rise is calculated on an hourly basis using the method of Briggs[6,7,8]. If the plume rise calculation indicates that the plume axis will rise above the mixing layer, then a zero concentration contribution is specified. If the final plume height is below the top of the mixing layer, the presence of the top of the layer is accounted for by the introduction of image plumes[5] to satisfy the zero flux conditions at ground level and at the top of the mixing layer. Source inputs to the model include stack height, diameter, gas exit velocity and gas temperature. Emission rates are input for each hour of the year.

The Meteorological Preprocessor Program output files for the Canal and Muskingum plants were analyzed to determine the frequency distributions of hourly wind speeds and mixing heights at each location. These distributions were then divided into three equal parts with the 33-1/3 and 66-2/3 percentile values given in Table 4a. Each of the three wind speed and mixing height classes represent one-third of the 8760 hours included in the simulation. The percentage breakdown of hours by stability class for each plant is given in Table 4b. Stability G was not included in the stratified breakdown of data. The preprocessor output file was then reread for both plants so that hourly values of stability (1 to 6), wind speed class (1 to 3) and mixing height class (1 to 3) could be calculated. These values were in turn used to generate subsets of measured and calculated concentration files for each of the stability, wind speed and mixing height classes.

Cumulative frequency distributions of measured and calculated concentrations were then generated for each of the data subsets and plotted on a log-probability scale.

Table 4a. PERCENTILE FOR WIND SPEED (ADJUSTED TO 7 METERS) AND MIXING HEIGHT STRATIFICATION

Plant	Canal		Muskingum River	
Percentile	33 1/3	66 2/3	33 1/3	66 2/3
Wind speed (m/sec)	2.6	4.0	1.6	2.4
Mixing height (m)	750	1250	800	1200

Table 4b. PERCENT OCCURENCE OF DIFFERENT STABILITIES FOR CANAL AND MUSKINGUM

	Percent	
Stability	Canal	Muskingum
A	0.4	1.4
B	5.0	9.1
C	12.2	12.8
D	54.8	44.4
E	10.1	7.2
F	6.3	7.2
G	11.2	17.9

SECTION IV

MODEL VALIDATION RESULTS

As an aid in the interpretation of the model validation results we should point out some of the relationships among the three meteorological variables used in our analysis-stability class, wind speed and mixing height. Atmospheric stability class, determined according to Turner's method,[4] is a strong function of the wind speed as can be seen from Table 5 which gives the stability class as a function of wind speed and net radiation index. The net radiation index depends upon the solar elevation angle, cloud cover and ceiling. Although the stability class is a function of the wind speed at 7 meters, the wind speed at the stack top is calculated by use of a stability dependent power law. The higher the stability class the greater the increase in wind speed with height. This stack top wind speed is used in the calculation of plume dilution and plume rise. The procedure for determination of hourly mixing heights based upon maximum and minimum mixing heights for the day is shown in Figure 4. For neutral and unstable conditions (stabilities A-D), the hourly mixing height is based upon an interpolation between maximum daily mixing heights, while for other stabilities the interpolation is carried out between minimum and maximum daily mixing heights.

The model validation results are presented in detail in 30 series of figures in Appendix A where cumulative frequency distributions of calculated and measured concentration are compared. The first set of comparisons for different stability, wind speed and mixing height classes are made with data from all receptor locations combined. This initial comparison provides a rough picture of the effect of the three variables upon validation results. It also increases the overall statistical significance of the results above that of the detailed breakdown by receptor direction provided later.

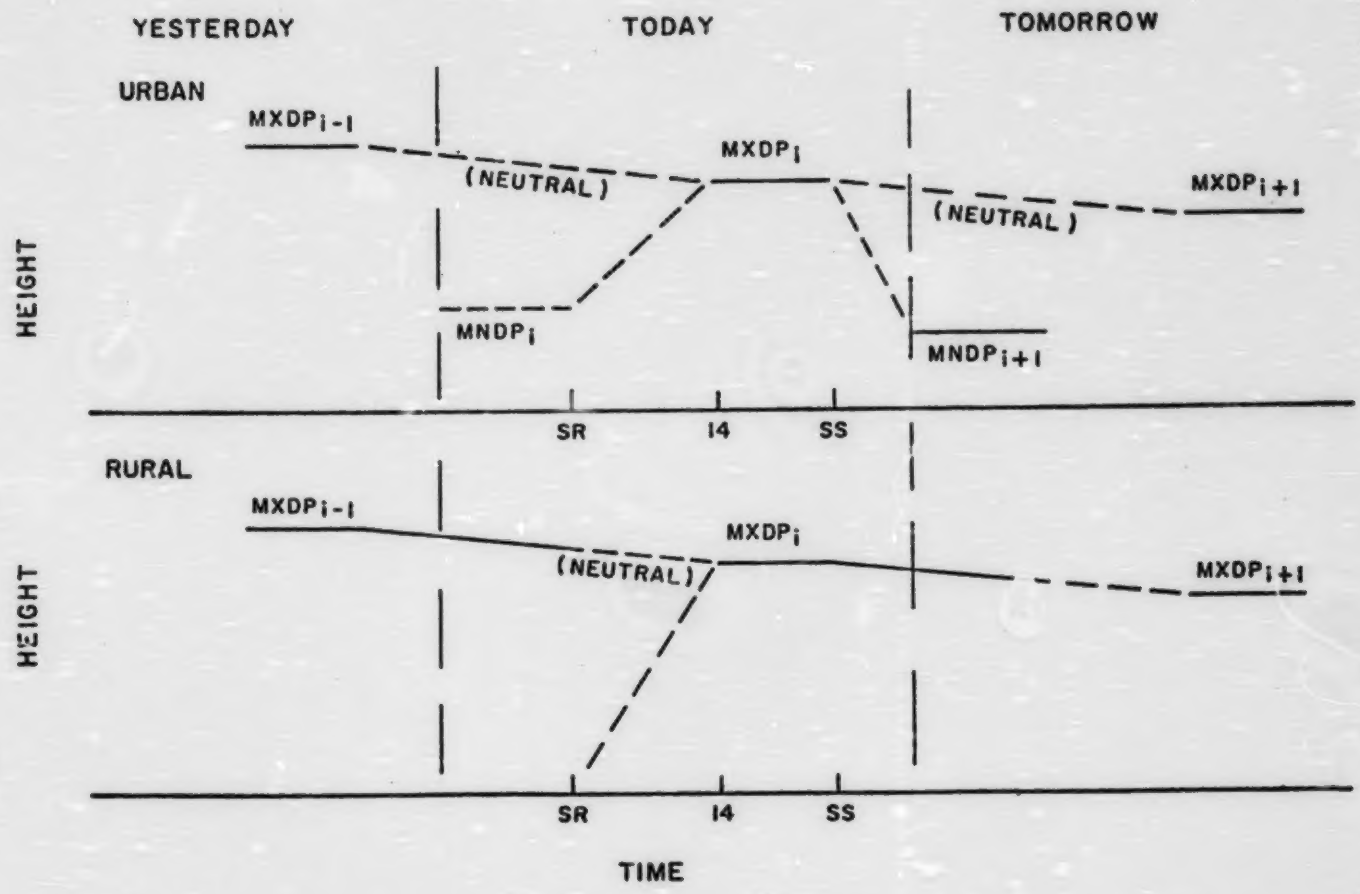
YESTERDAY
TODAY
TOMORROW
URBAN
MXDP$_{i-1}$
MXDP$_i$
(NEUTRAL)
MXDP$_{i+1}$
(NEUTRAL)
MNDP$_i$
MNDP$_{i+1}$
HEIGHT
SR
14
SS
RURAL
MXDP$_{i-1}$
MXDP$_i$
(NEUTRAL)
MXDP$_{i+1}$
HEIGHT
SR
14
SS
TIME

Figure 4. Determination of hourly mixing heights

Table 5. STABILITY CLASS AS A FUNCTION OF NET RADIATION AND WIND SPEED

Wind speed, knots	Net radiation index						
	4	3	2	1	0	-1	-2
0,1	1	1	2	3	4	6	7
2,3	1	2	2	3	4	6	7
4,5	1	2	3	4	4	5	6
6	2	2	3	4	4	5	6
7	2	2	3	4	4	4	5
8,9	2	3	3	4	4	4	5
10	3	3	4	4	4	4	5
11	3	3	4	4	4	4	4
≥12	3	4	4	4	4	4	4

Model validation results at the Canal Plant (four stations combined) for stabilities 1 through 6 are shown in Figures A-1a through A-1f. The most striking feature of these comparisons is the strong tendency of the Single Source Model to underpredict 1-hour concentrations for stabilities D through F. The same trend toward underprediction for the higher stabilities was also found for the Muskingum Plant (Figures A-2a through A-2f) but the overprediction for stabilities A through C is enough to achieve an overall agreement. For the higher wind speed classes at the Canal plant the greater degree of underprediction is probably due to the higher stabilities (see Figures A-3a through A-3c). At the Muskingum Plant, on the other hand, there is a tendency to overpredict for higher wind speed which may indicate a problem with the plume rise estimates at this facility but the evidence is far from conclusive (see Figures A-4a through A-4c). For the Canal Plant there does not appear to be a definite pattern to the degree of model underprediction and mixing height class (see Figures A-5a through A-5c). For mixing height class 3 the calculated and measured concentration distributions agree reasonably well. This also was the case for stability classes A through C. An analysis of the model validation results for the Muskingum Plant for different mixing height classes (Figures A-6a through A-6c) reveals a strong underprediction for mixing height class 1. This result indicates that either the mixing height for this area is being underestimated or that the assumption of complete plume penetration of the top of the mixing layer is in error.

A more detailed picture of the model validation results for the stratified concentration data may be obtained through an examination of Figures A-7a through A-30d which give a receptor by receptor comparison of measured and calculated concentration distributions for different stabilities, wind speed classes and mixing height classes. Rather than discuss the results shown in each figure, we have instead presented our findings in Table 6. For each plant, receptor and meteorological parameter we have indicated whether the model overpredicted, underpredicted or agreed with the measured concentration distribution. In this rather qualitative classification of the model validation results, the comparison was made at the upper end of the frequency distribution (beyond the 99th percentile). Based upon these results we may summarize our findings as follows:

- The frequency distributions for both Canal and Muskingum plants show a tendency toward overprediction for stabilities A and B, especially for those receptors closest to the plant.
- At both the Canal and Muskingum plants there is a strong tendency for the model to underpredict for stabilities D, E and F. For stability C, the model predictions agree relatively well with measured concentrations.
- The strong underprediction at Canal for stability D is even more serious in light of the fact that the measured concentrations, corrected for background, are the highest for this stability assignment.
- At the Canal Plant there is a greater tendency for model underprediction for higher wind speeds. This result is consistent with the model underprediction for higher

stabilities. On the other hand the opposite trend is observed for the Muskingum Plant, which may indicate that either plume rise or terrain effects are not being handled properly.

- No general trend could be discerned from the comparison of measured and calculated concentration frequency distributions by mixing height. In the case of the Muskingum Plant the agreement for the second and third mixing height classes was relatively good, while the model definitely underpredicted concentrations for the lowest group of mixing heights. This could point to a problem with the assumption regarding complete plume penetration of the top of the mixing layer or an error in the mixing height assignment itself.

Table 6. MODEL VALIDATION RESULTS FOR ALL PLANTS, RECEPTORS AND METEOROLOGICAL CONDITIONS (O = OVERPREDICTION, U = UNDERPREDICTION, A = AGREEMENT, I = INCONCLUSIVE DUE TO INSUFFICIENT DATA)

Meteorological variable	Class	Plant	Receptor				
			1	2	3	4	All
Stability							
		Canal					
	A		I	I	O	I	O
	B		U	U	A	I	A
	C		A	A	U	U	A
	D		U	U	U	U	U
	E		U	U	U	U	U
	F		U	U	U	U	U
		Muskingum					
	A		O	O	A	U	O
	B		A	O	A	A	O
	C		U	A	A	A	A
	D		U	U	U	A	U
	E		U	U	U	U	U
	F		U	U	U	U	U
Wind speed							
		Canal					
	1		U	U	O	U	A
	2		U	U	O	U	U
	3		U	U	U	U	U
		Muskingum					
	1		U	U	U	A	U
	2		A	O	A	A	A
	3		A	O	A	A	O
Mixing height							
		Canal					
	1		U	U	U	U	U
	2		U	U	U	U	U
	3		U	U	O	U	A
		Muskingum					
	1		U	U	U	U	U
	2		A	O	A	A	A
	3		A	O	A	A	A

SECTION V

CONCLUSIONS AND RECOMMENDATIONS

The most obvious conclusion of this study is that the dispersion curves and stability assignment procedure currently used in the Single Source Model leads to model overprediction for the unstable conditions and underprediction for the more stable conditions. This trend is most clearly shown in the model validation results for the Muskingum Plant where the upper ends of the calculated and measured concentration frequency distributions cross one another for stability Class C (Figure A-2c). For both Canal and Muskingum plants, the model strongly underpredicts for stability D. At the Muskingum plant the measured concentration frequency distributions for stabilities C and D are quite similar while the predicted distribution curve for stability D falls considerably below that for stability C. This effect is even more pronounced for the Canal plant with the stability D concentration distribution actually rising above that for stability C. The underprediction at the Muskinghum plant for stabilities E and F does not appear to be a serious problem since the characteristics of the distributions for these lower concentrations are greatly affected by uncertainties in the background subtraction procedure. At the Canal plant, however, the frequency of stable conditions would appear to be much less than that determined through the Pasquill-Turner stability assignment procedure. Based upon these results we would recommend that C and D stabilities be combined into a single class with σ_y and σ_z dispersion curves closer to that currently used for stability C. At the same time the σ_z values for stabilities A and B should be reduced slightly to avoid model overprediction during unstable conditions.

The conclusions based upon the model validation results for different wind speed classes must be more tentative. The trend toward greater model underprediction at Canal for higher wind speeds is probably directly related to a similar trend toward underprediction for the high stabilities. The overprediction at Muskingum for the higher wind speeds is more difficult to understand since the trend toward underprediction for higher stabilities was also present for this plant. A possible explanation is that during light winds the zero level displacement assumption used in the model is valid but for higher winds this assumption breaks down. The only definite conclusion which was reached based upon the model validation for different mixing height classes was that the underprediction at Muskingum for the lowest mixing height class was due either to an underestimate in the hourly mixing height or a breakdown in the assumption of complete plume penetration of the top of the mixing layer.

SECTION VI

REFERENCES

1. Mills, M. T. and F. A. Record. Comprehensive Analysis of Time Concentration Relationships and the Validation of a Single Source Dispersion Model. Publication Number EPA-450/3-75-083. Prepared by GCA/Technology Division for the U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. March 1975.

2. Mills, M. T. and R. W. Stern. Model Validation and Time-Concentration Analysis of Three Power Plants. Publication Number EPA-450/3-76-002. Prepared by GCA/Technology Division for the U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. December 1975.

3. Mills, M. T., R. W. Stern and L. M. Vincent. Improvement to the Single Source Model. Volume II - Testing and Evaluation of Model Improvements. Final Report. EPA Contract No. 68-02-1376, Task Order No. 23. Prepared by GCA/Technology Division for the U.S. Environmental Protection Agency, Research Triangle Park, North Carolina. January 1977.

4. Turner, D. B. A Diffusion Model for an Urban Area. J Appl Meteor 3:83-91. February 1969.

5. Turner, D. B. Workbook of Atmospheric Dispersion Estimates. U.S. Environmental Protection Agency, Office of Air Programs. Publication Number AP-26.

6. Briggs, G. A. Plume Rise USAEC Critical Review Series TID-25075, National Technical Information Service, Springfield, Va. 22151. 1969.

7. Briggs, G. A. Some Recent Analyses of Plume Rise Observation, pp. 1029-1032, in Proceedings of the Second International Clean Air Congress, edited by H. M. Englund and W. T. Berry. Academic Press, New York. 1971.

8. Briggs, G. A. Discussion on Chimney Plumes in Neutral and Stable Surroundings. Atmos. Environ. 6, 507-510. July 1972.

APPENDIX A

CUMULATIVE FREQUENCY DISTRIBUTIONS

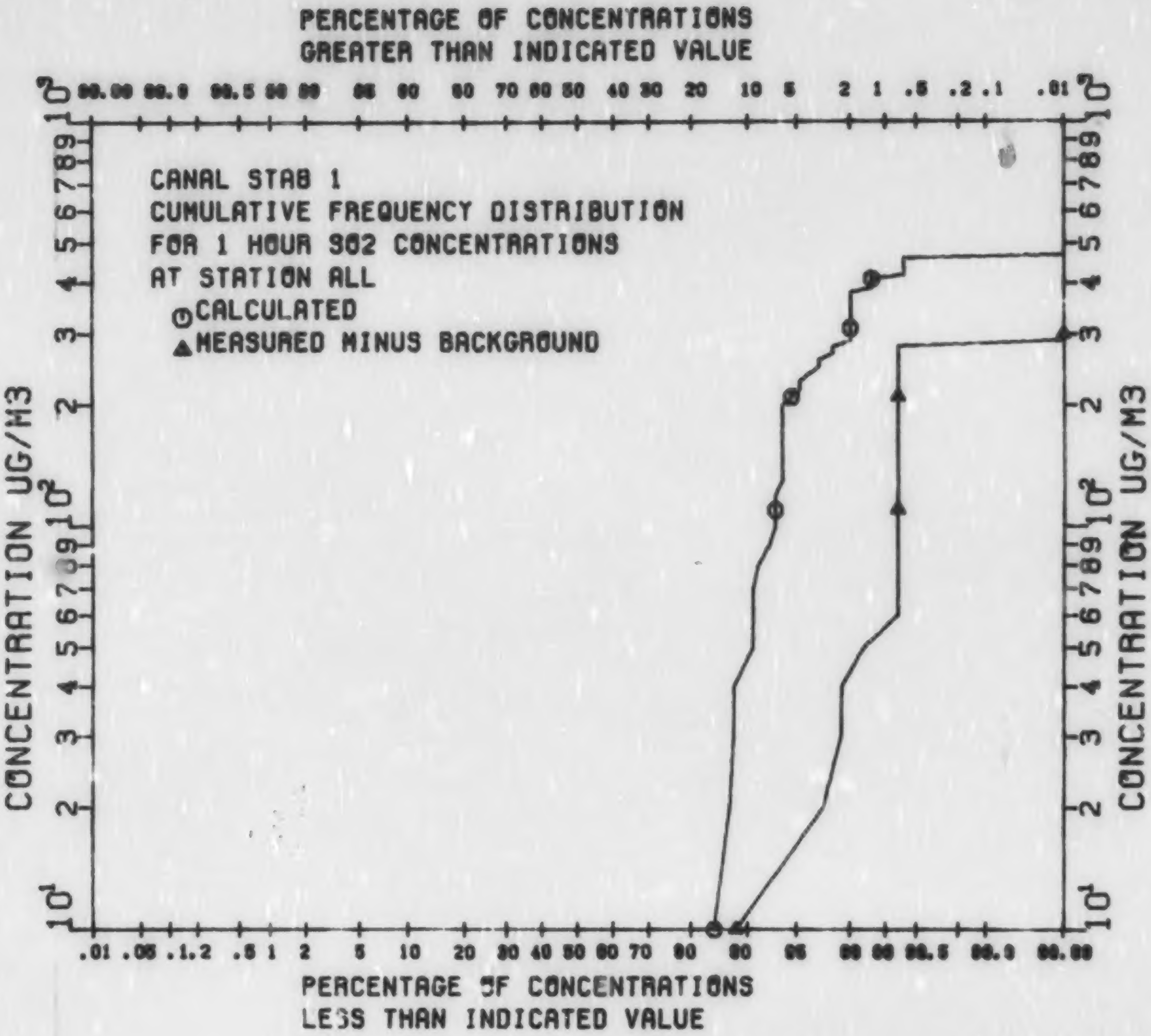

Figure A-1a. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for all receptors for stability A

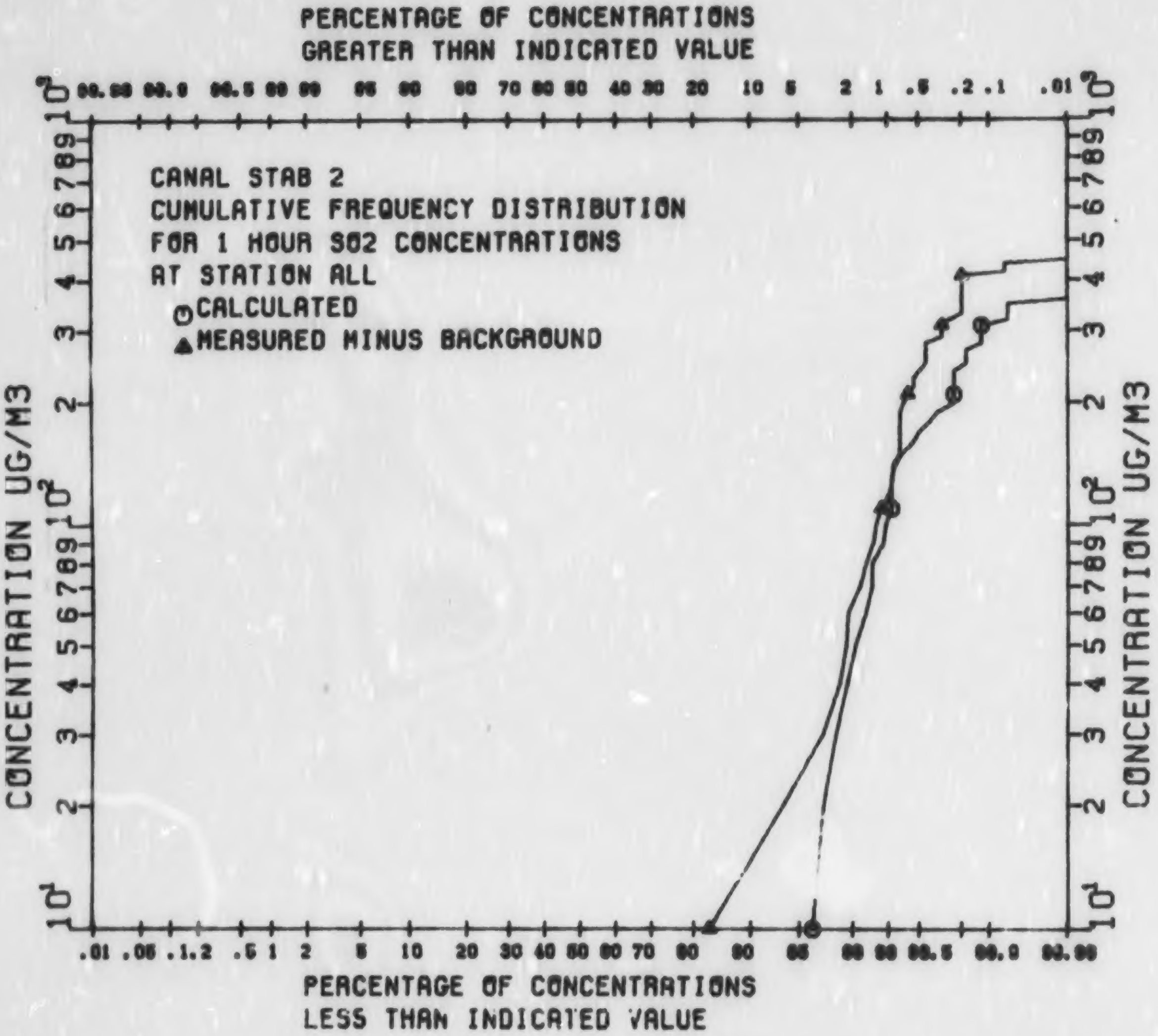

Figure A-1b. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for all receptors for stability B

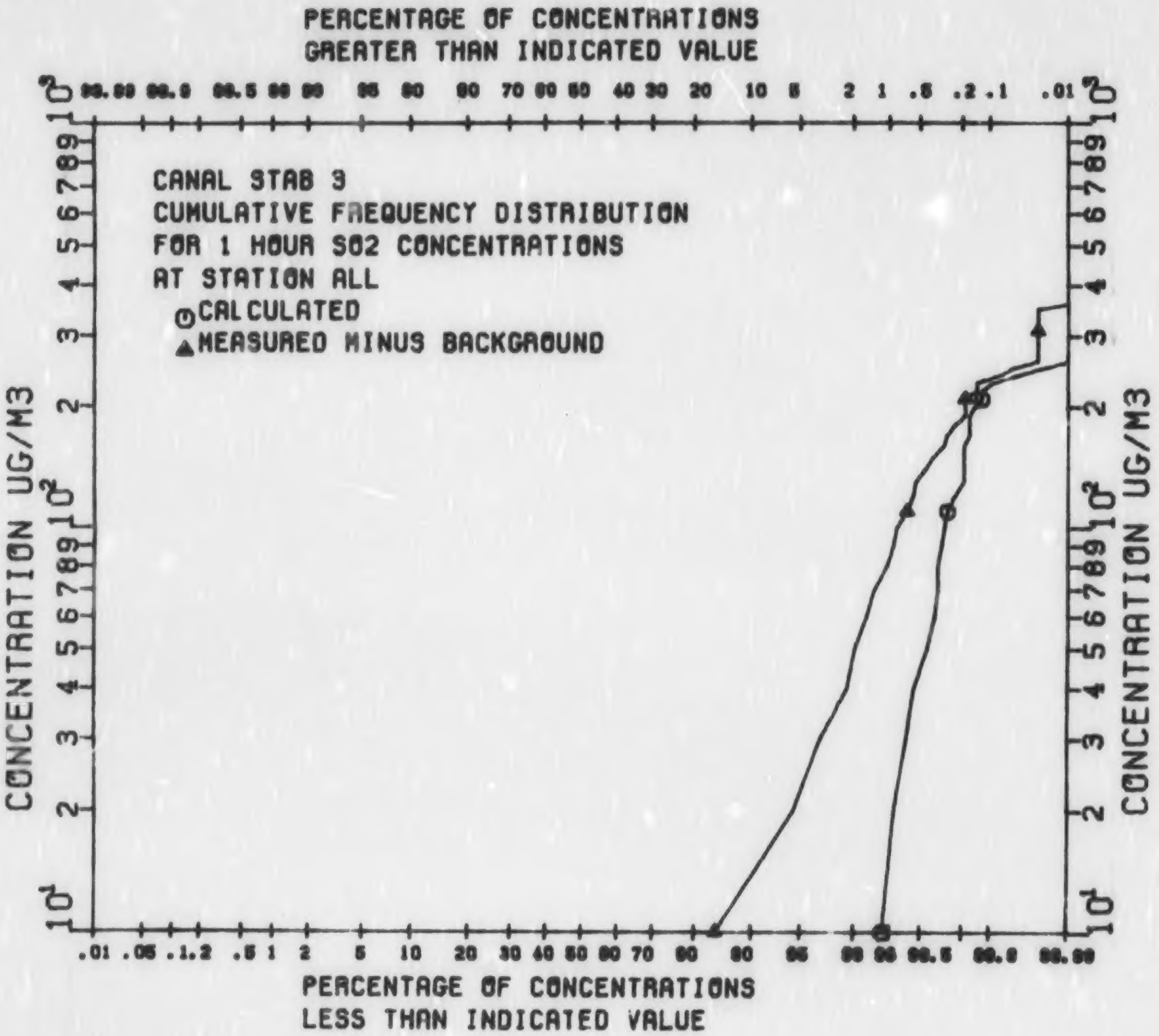

Figure A-1c. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for all receptors for stability C

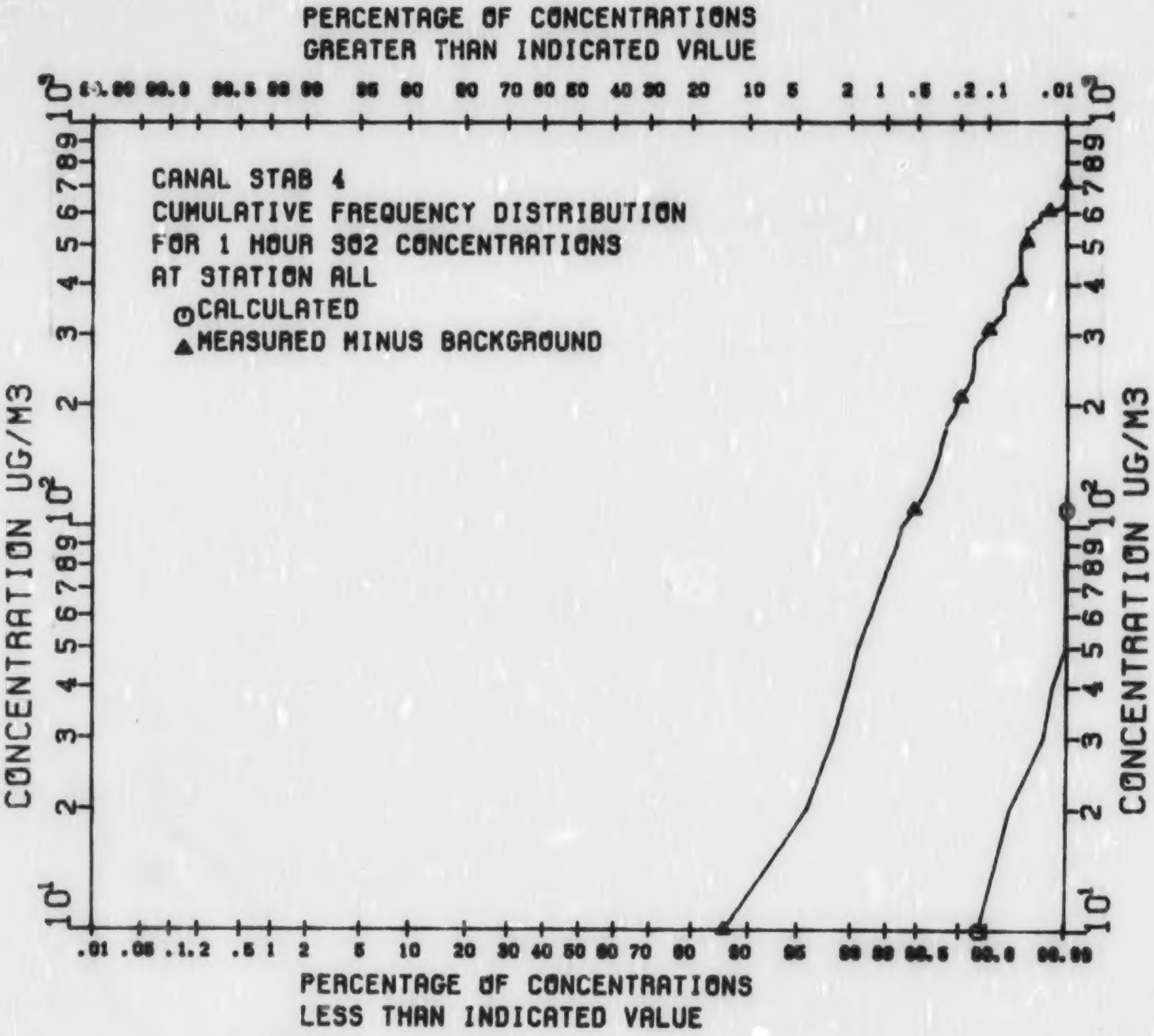

Figure A-1d. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for all receptors for stability D

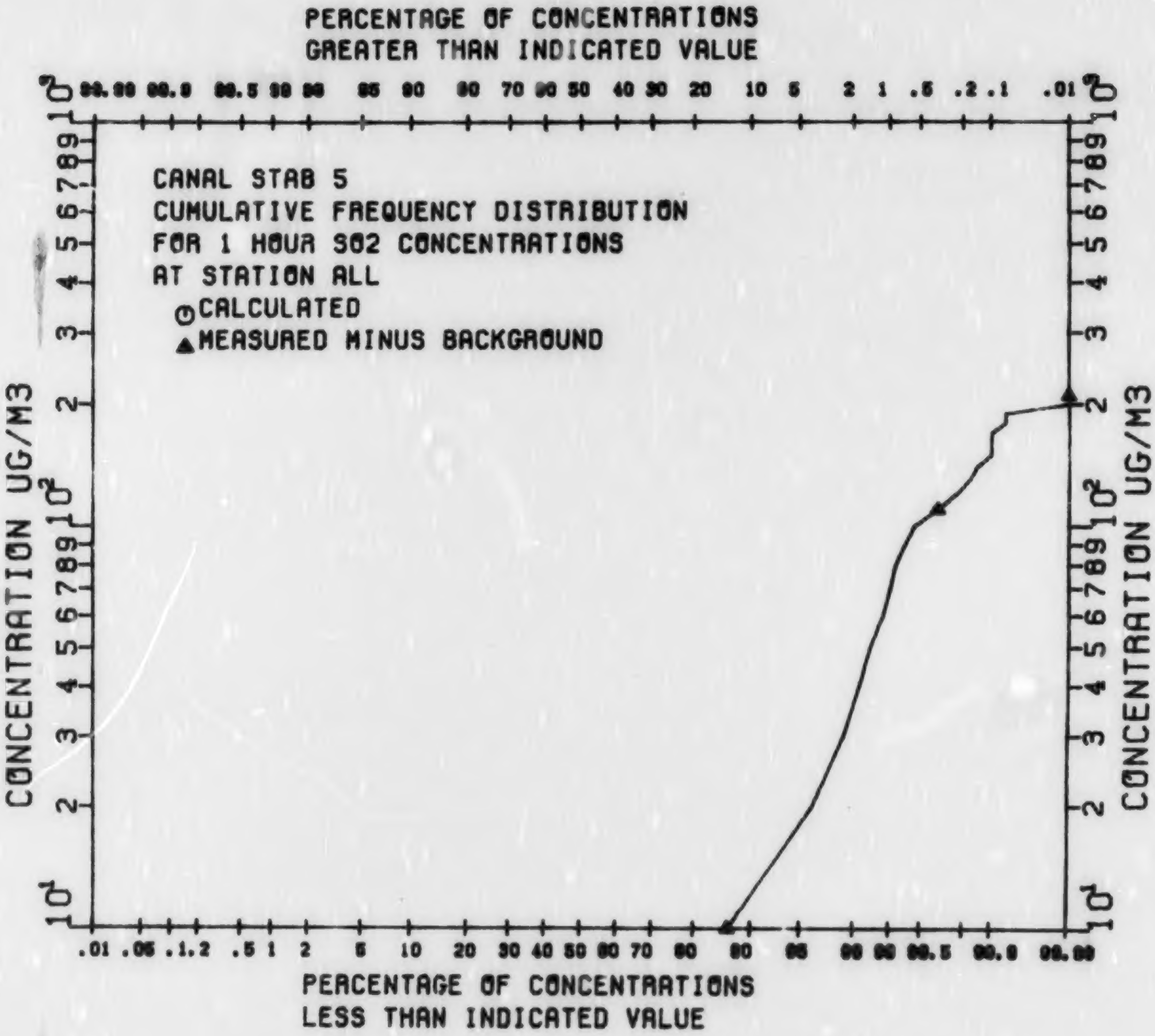

Figure A-1e. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for all receptors for stability E

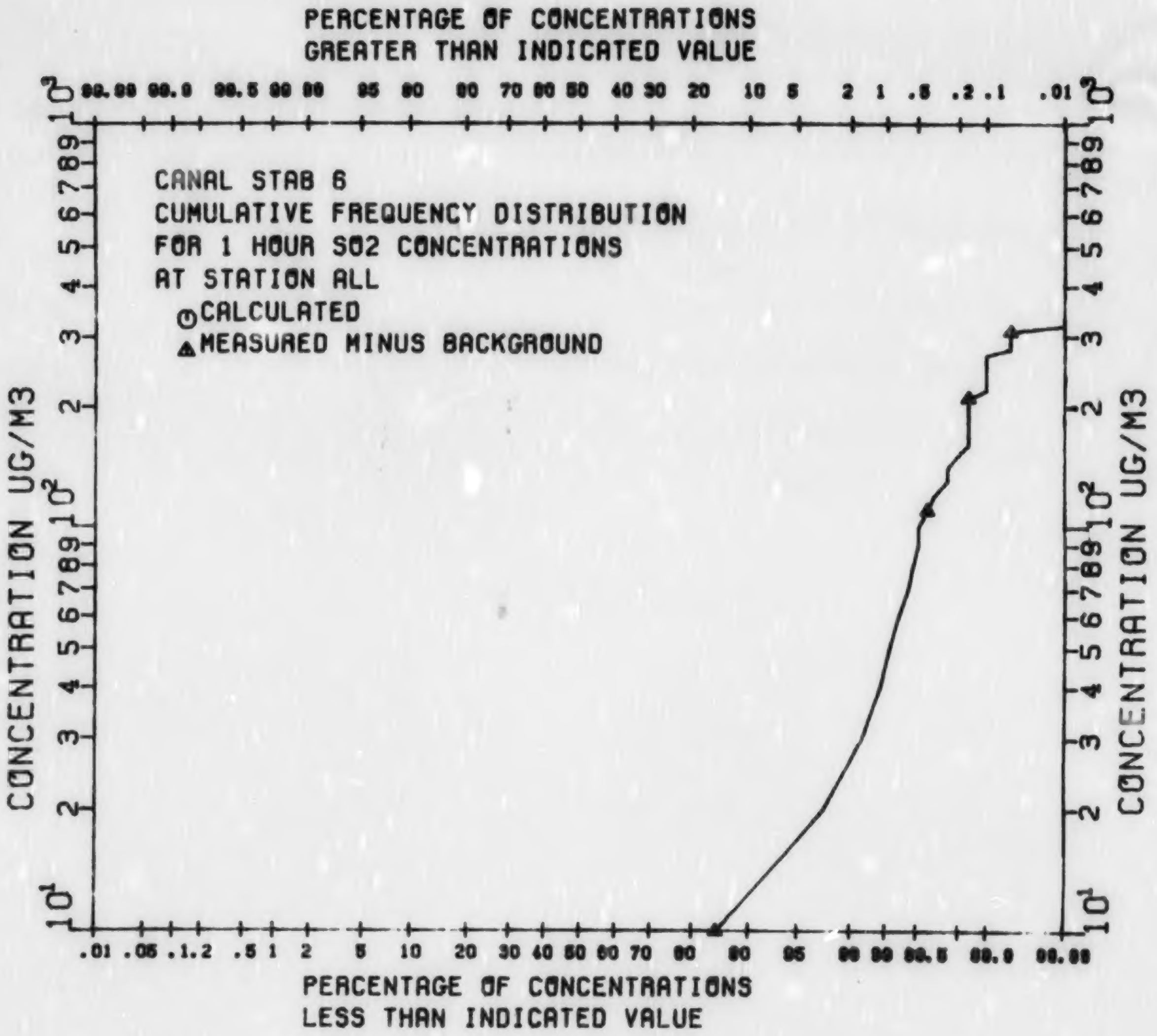

Figure A-1f. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for all receptors for stability F

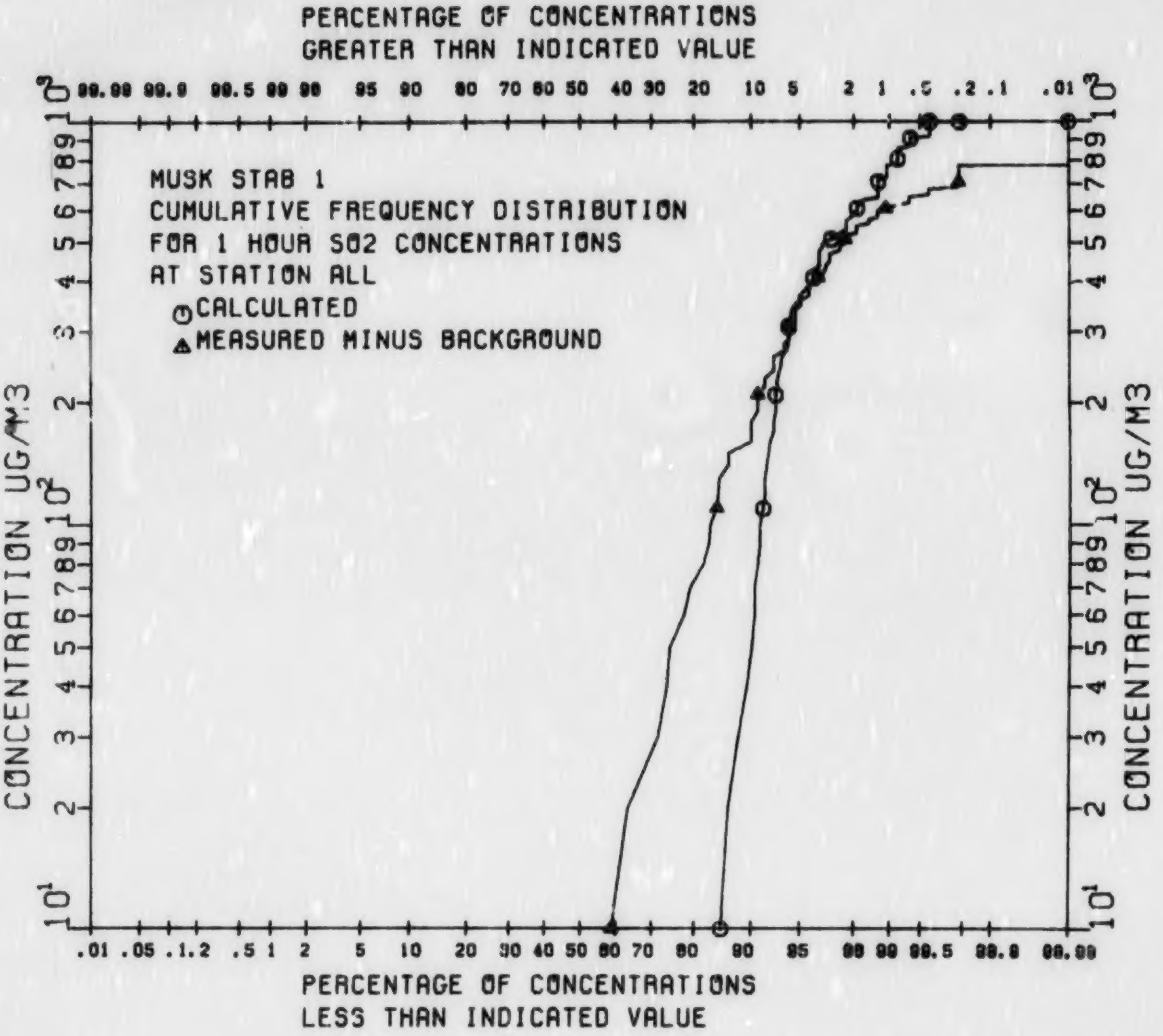

Figure A-2a. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for all receptors for stability A

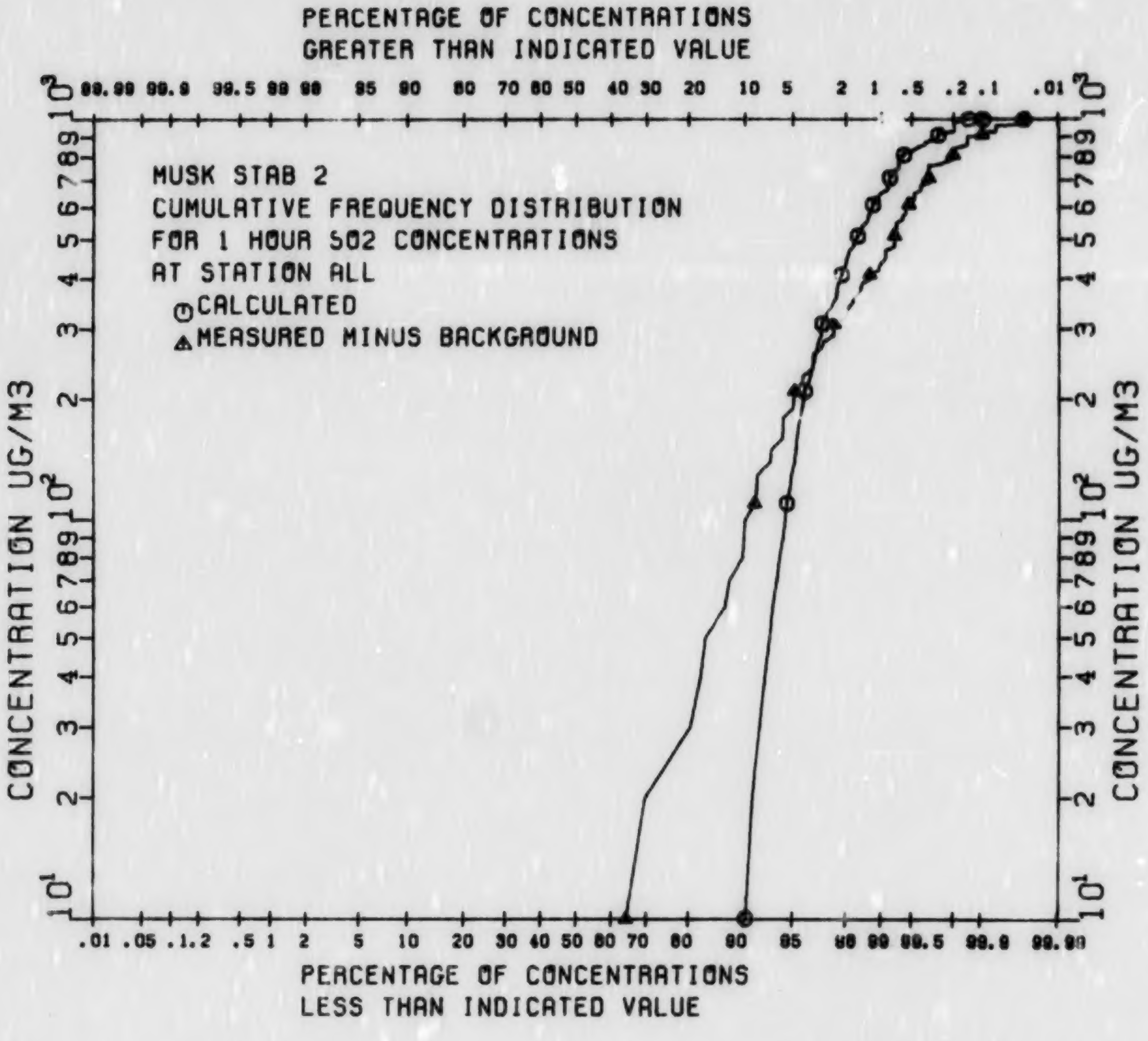

Figure A-2b. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for all receptors for stability B

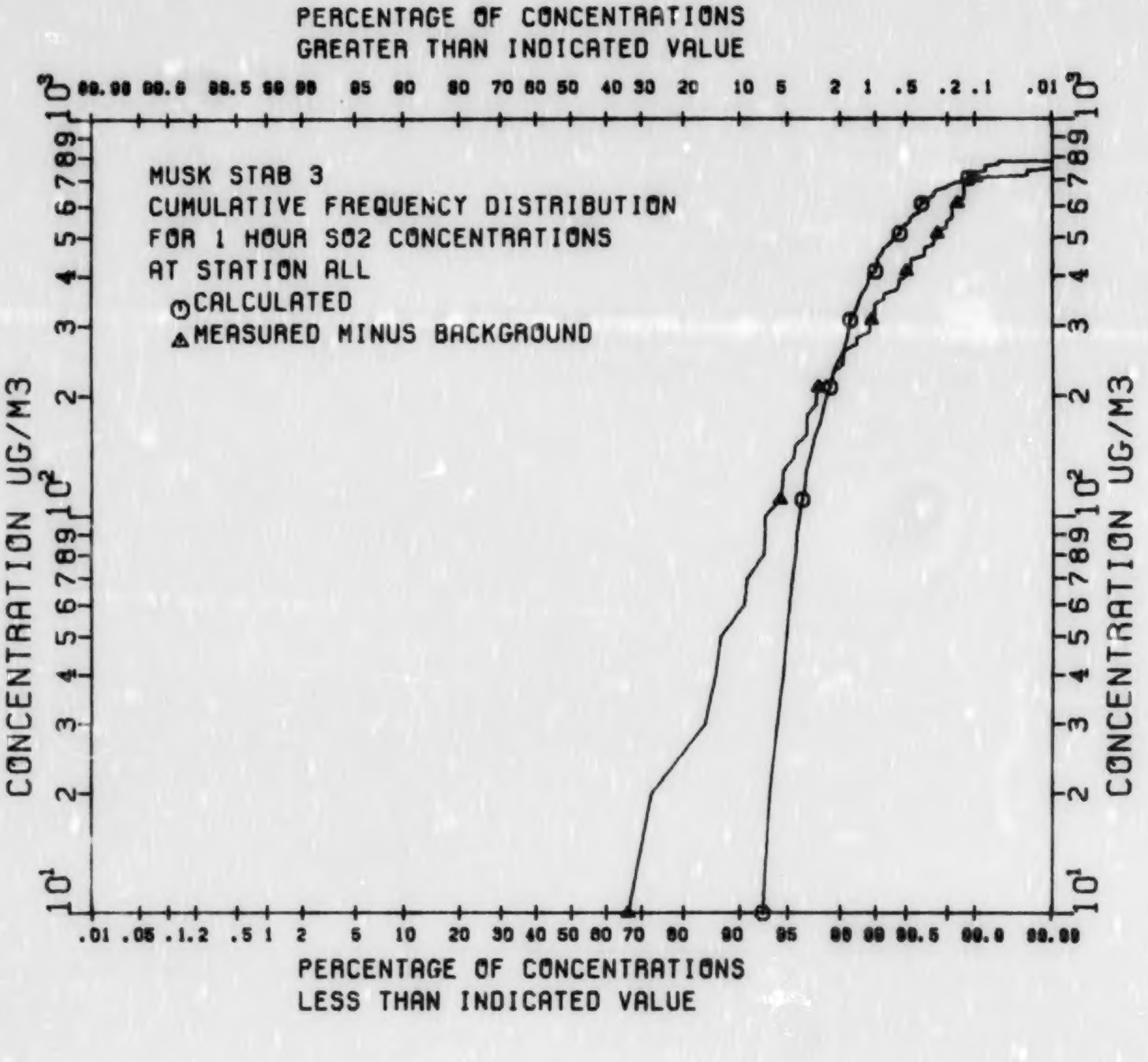

Figure A-2c. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for all receptors for stability C

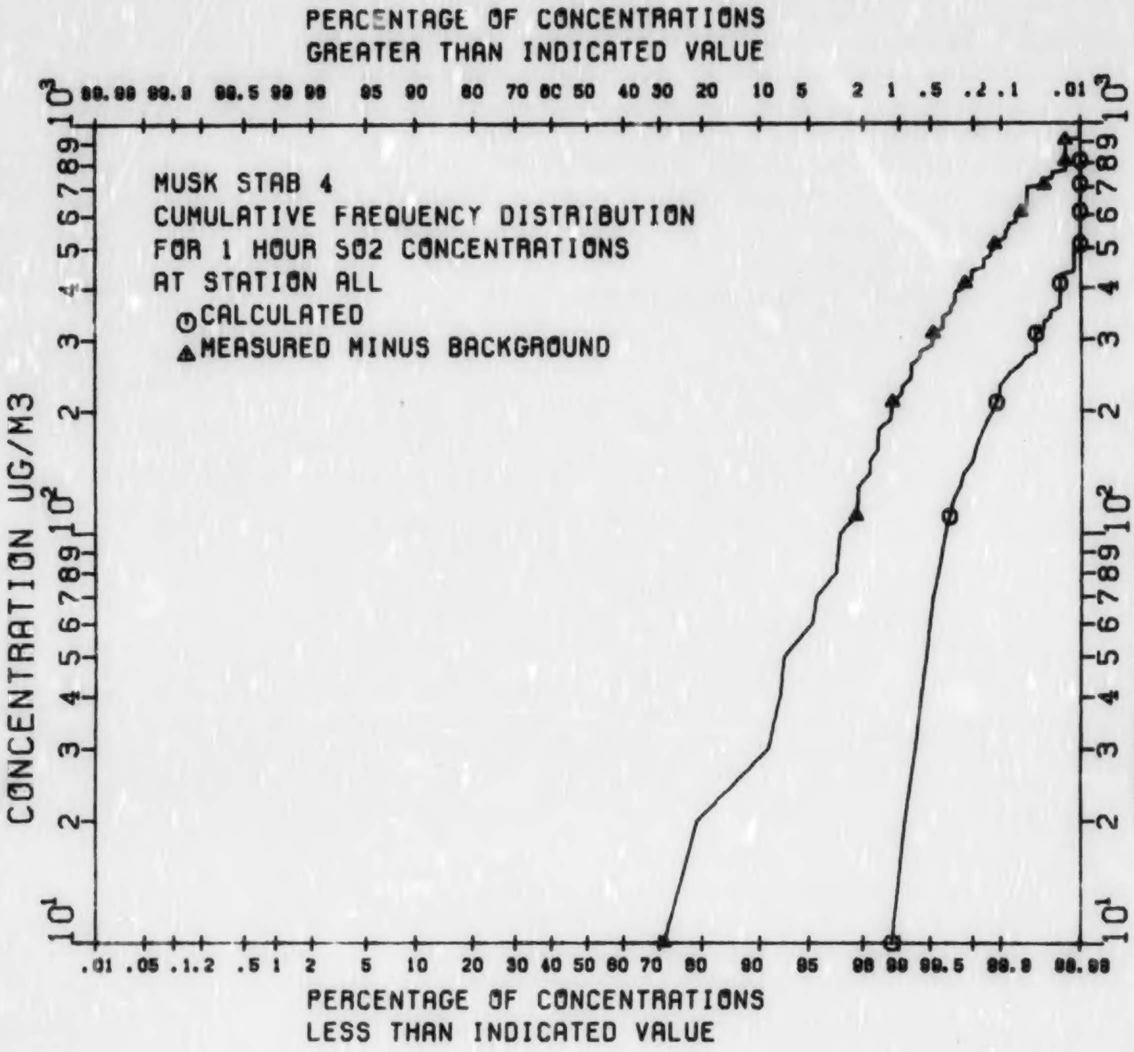

Figure A-2d. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for all receptors for stability D

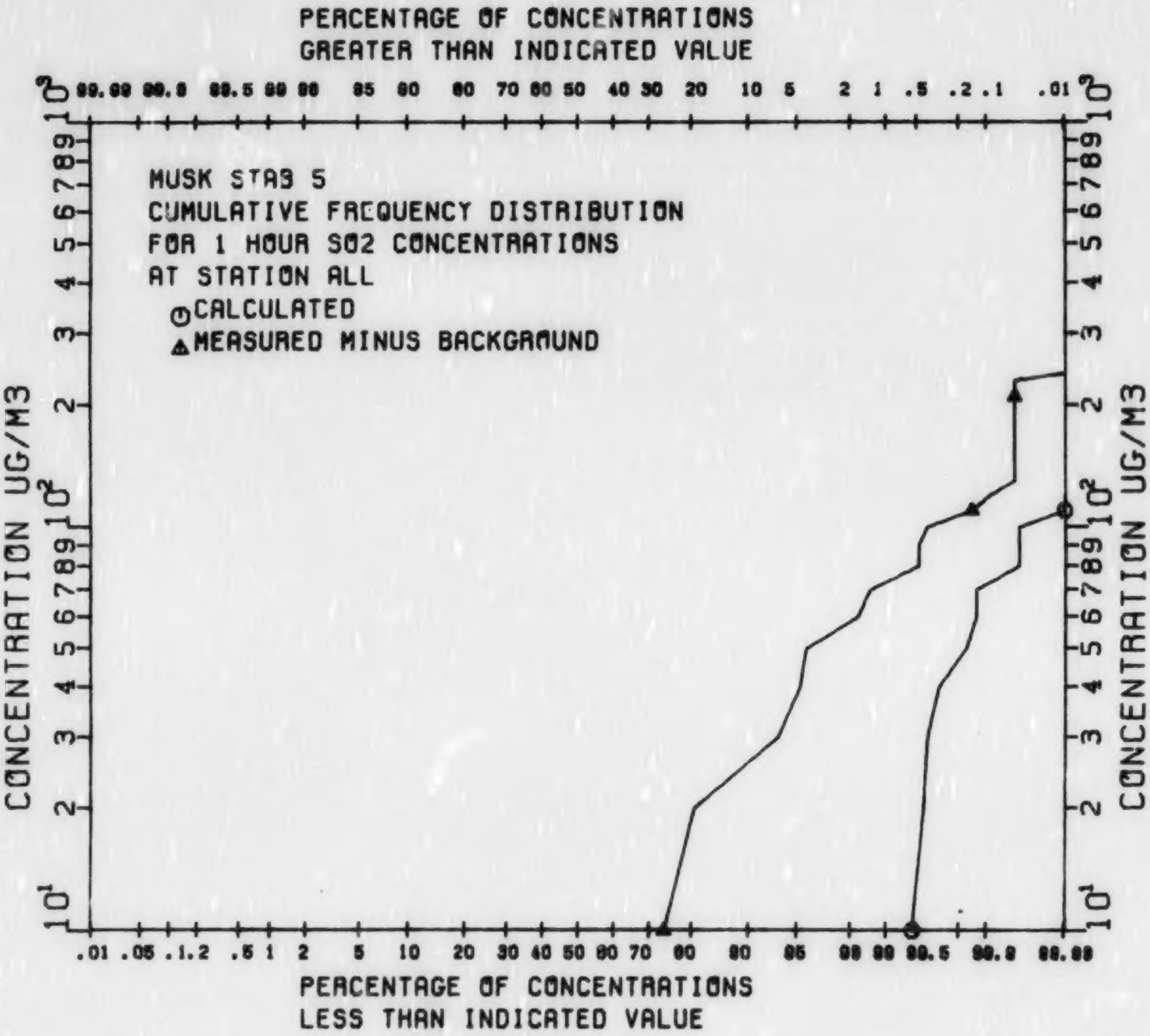

Figure A-2e. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for all receptors for stability E

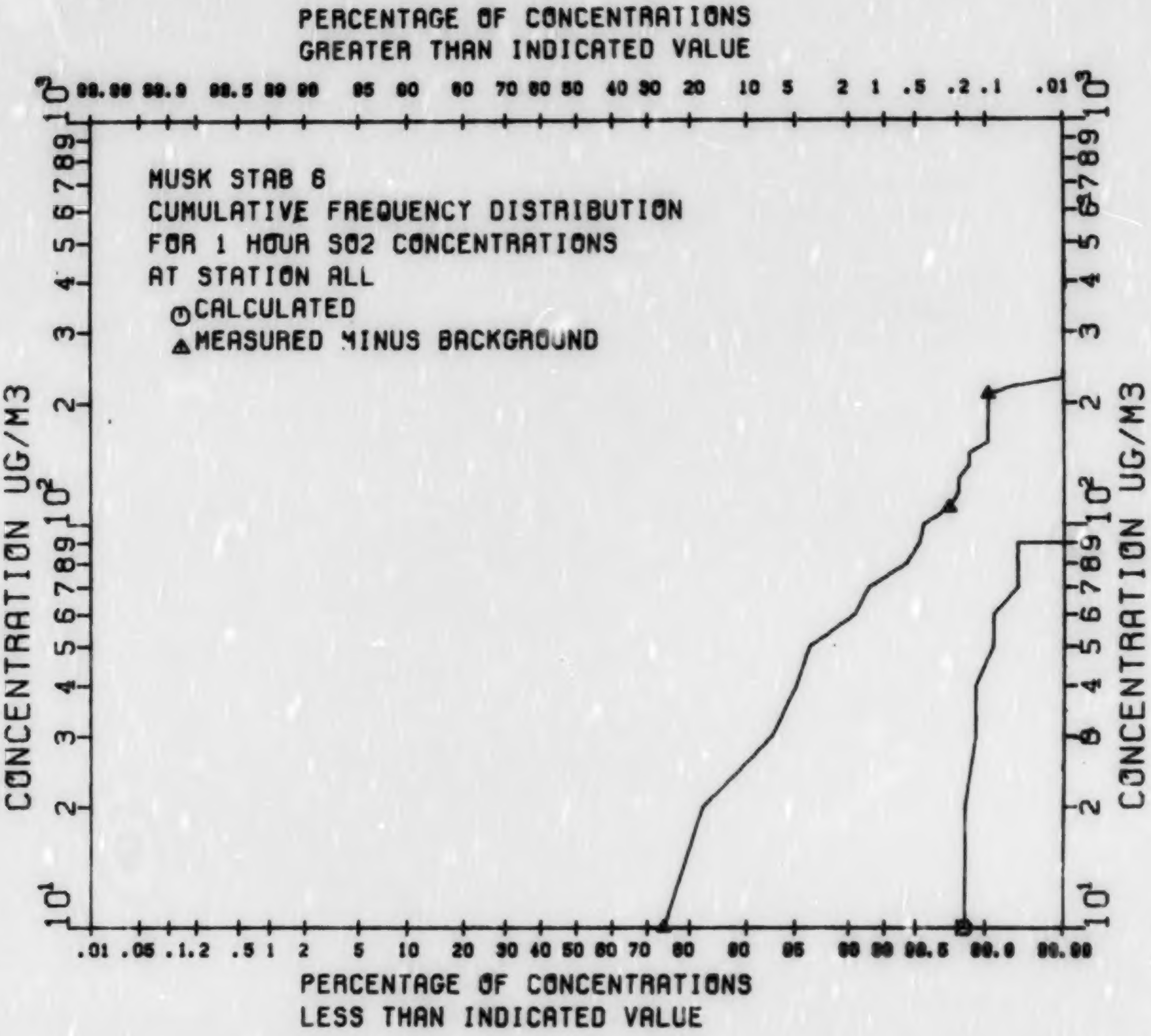

Figure A-2f. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for all receptors for stability F

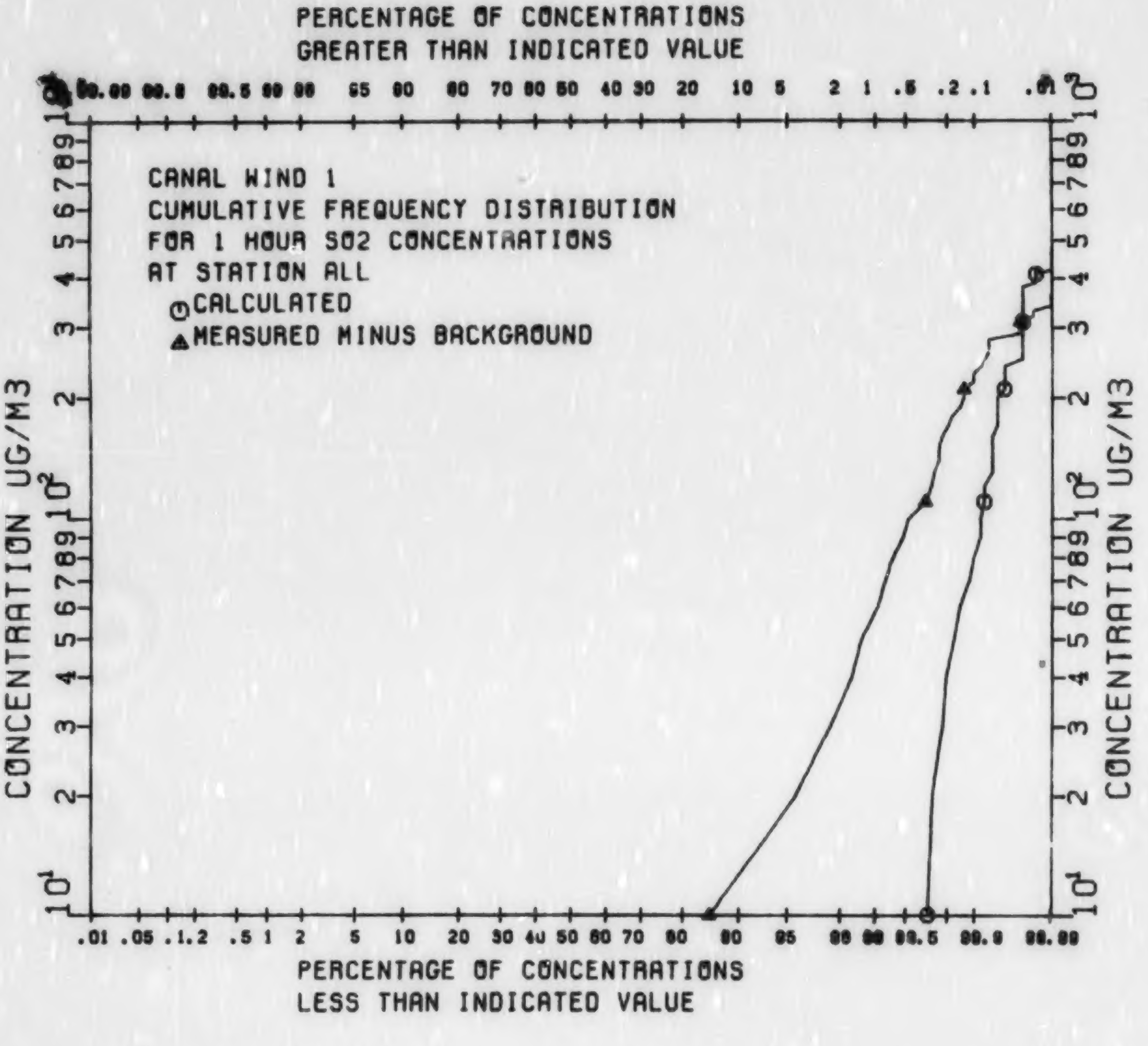

Figure A-3a. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for all receptors for wind speed class 1 (0 to 2.6 m/sec)

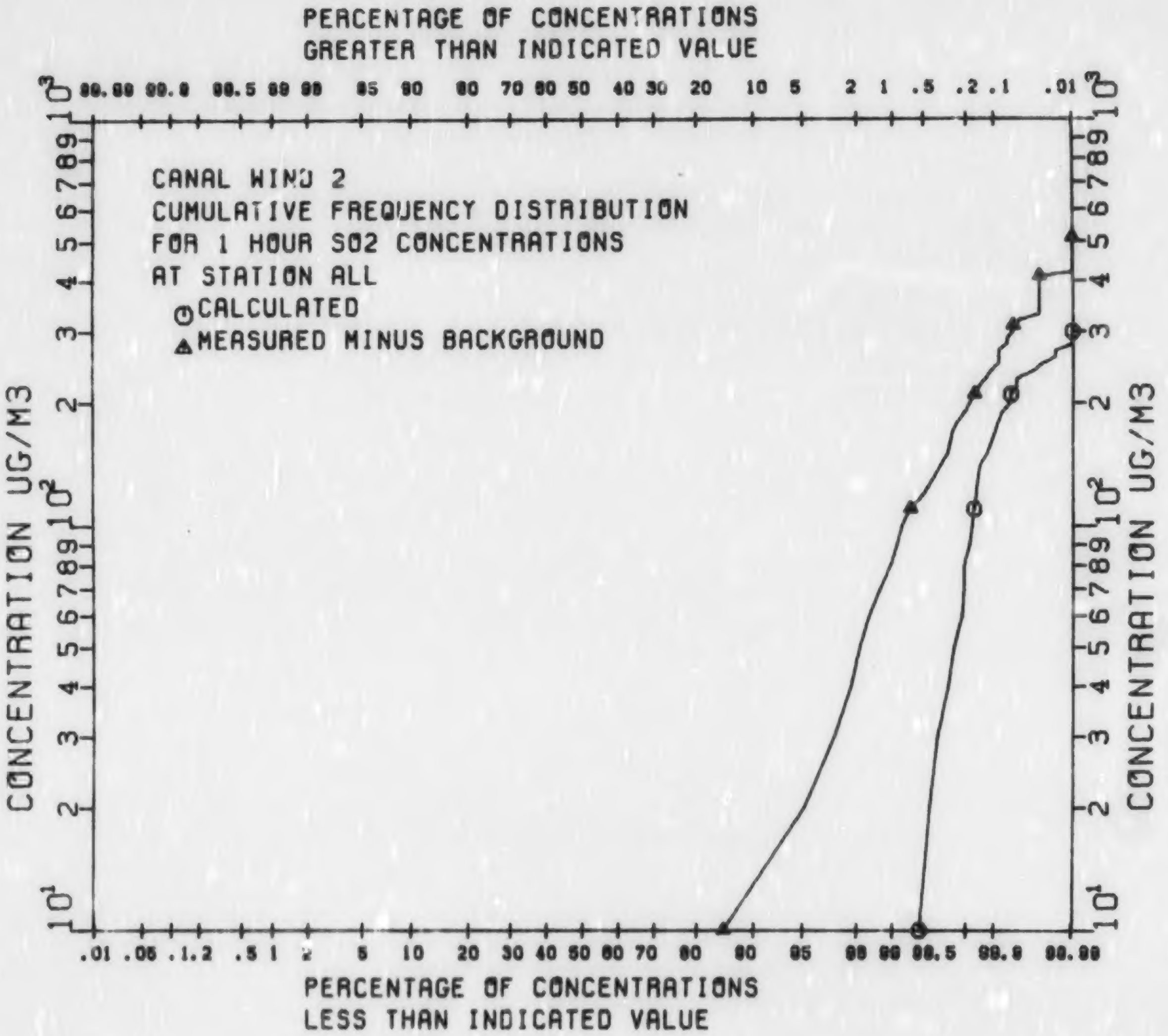

Figure A-3b. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for all receptors for wind speed class 2 (2.6 to 4.0 m/sec)

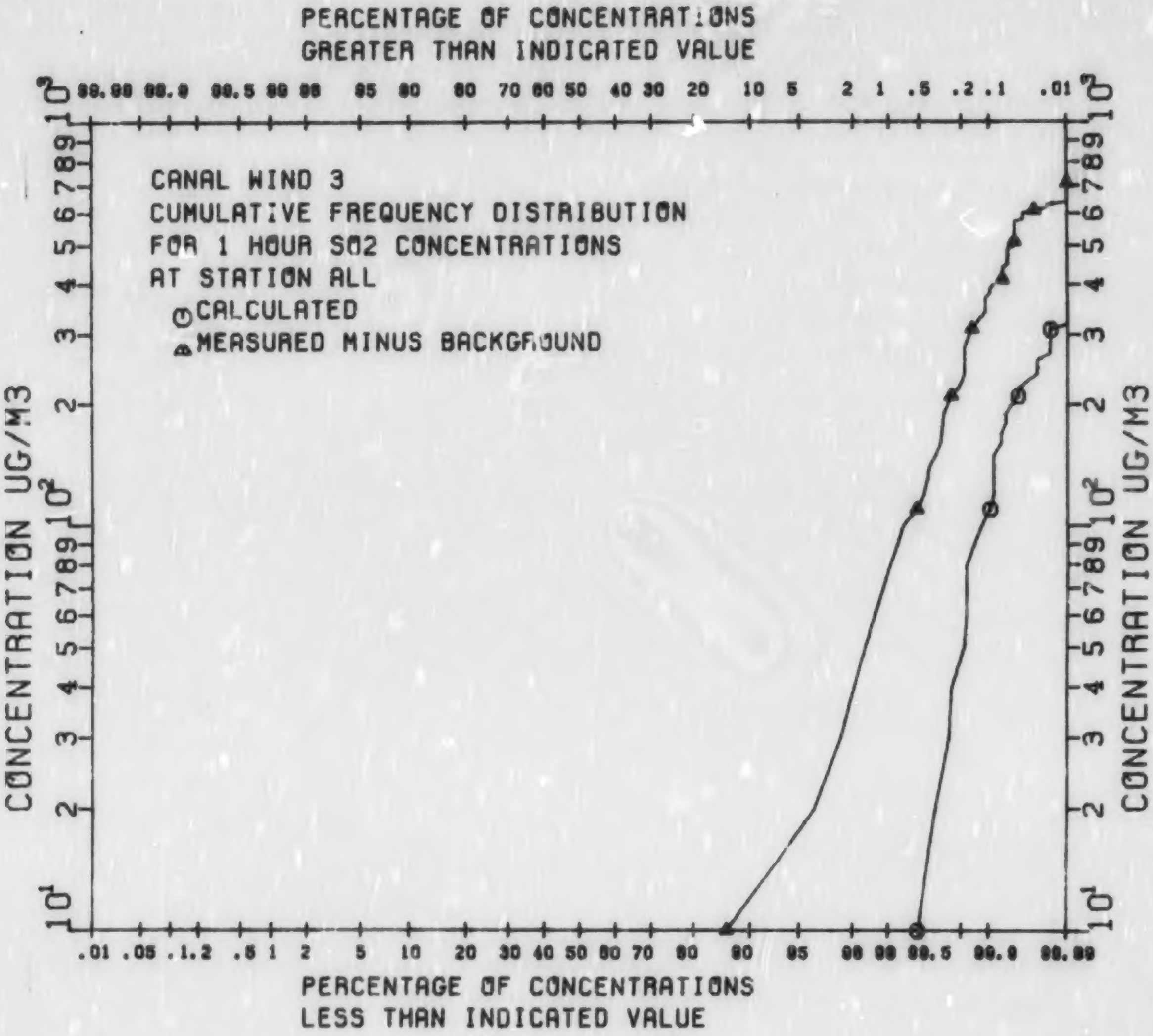

Figure A-3c. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for all receptors for wind speed class 3 (4.0 m/sec)

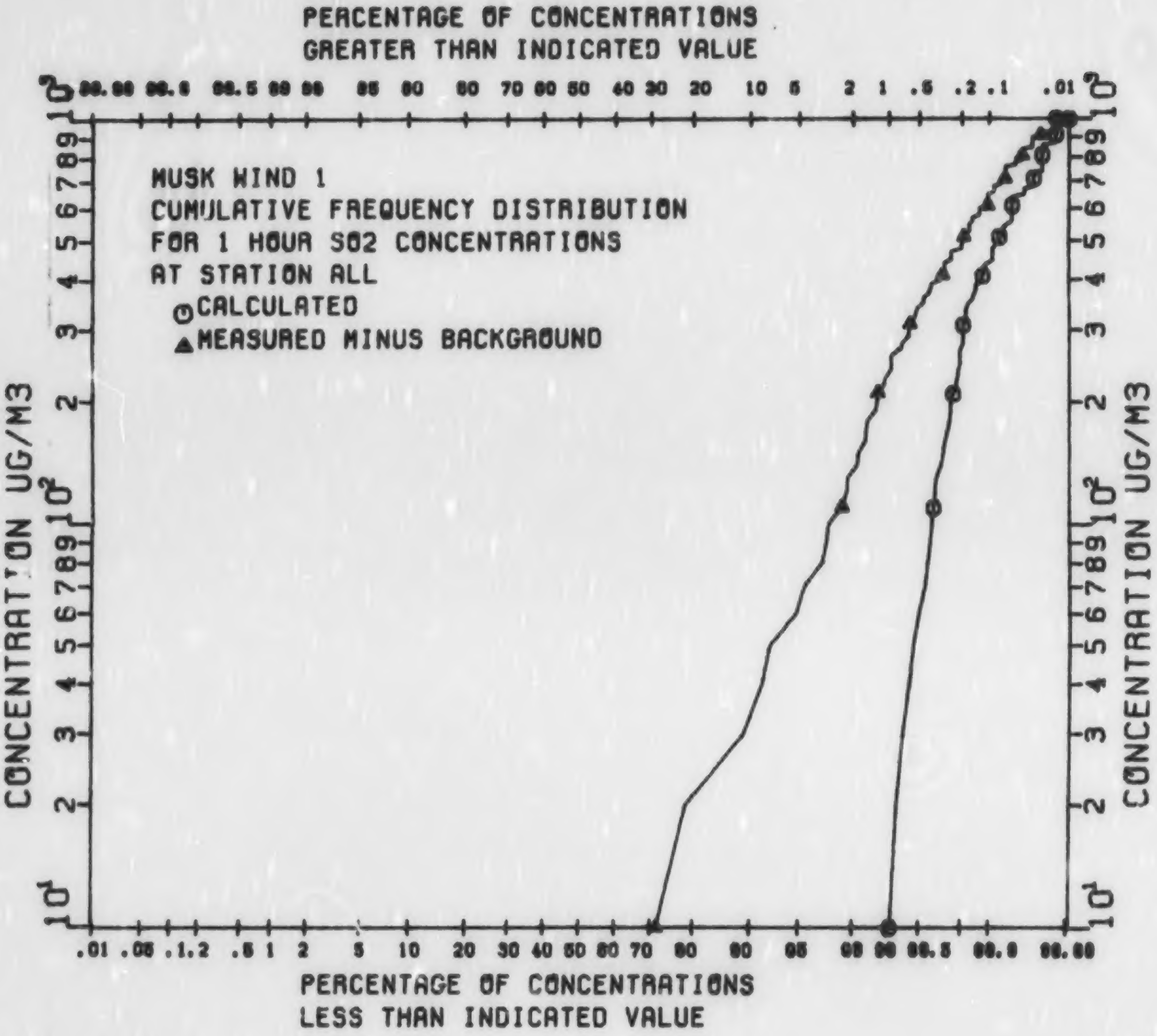

Figure A-4a. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for all receptors for wind speed class 1 (0 to 1.6 m/sec)

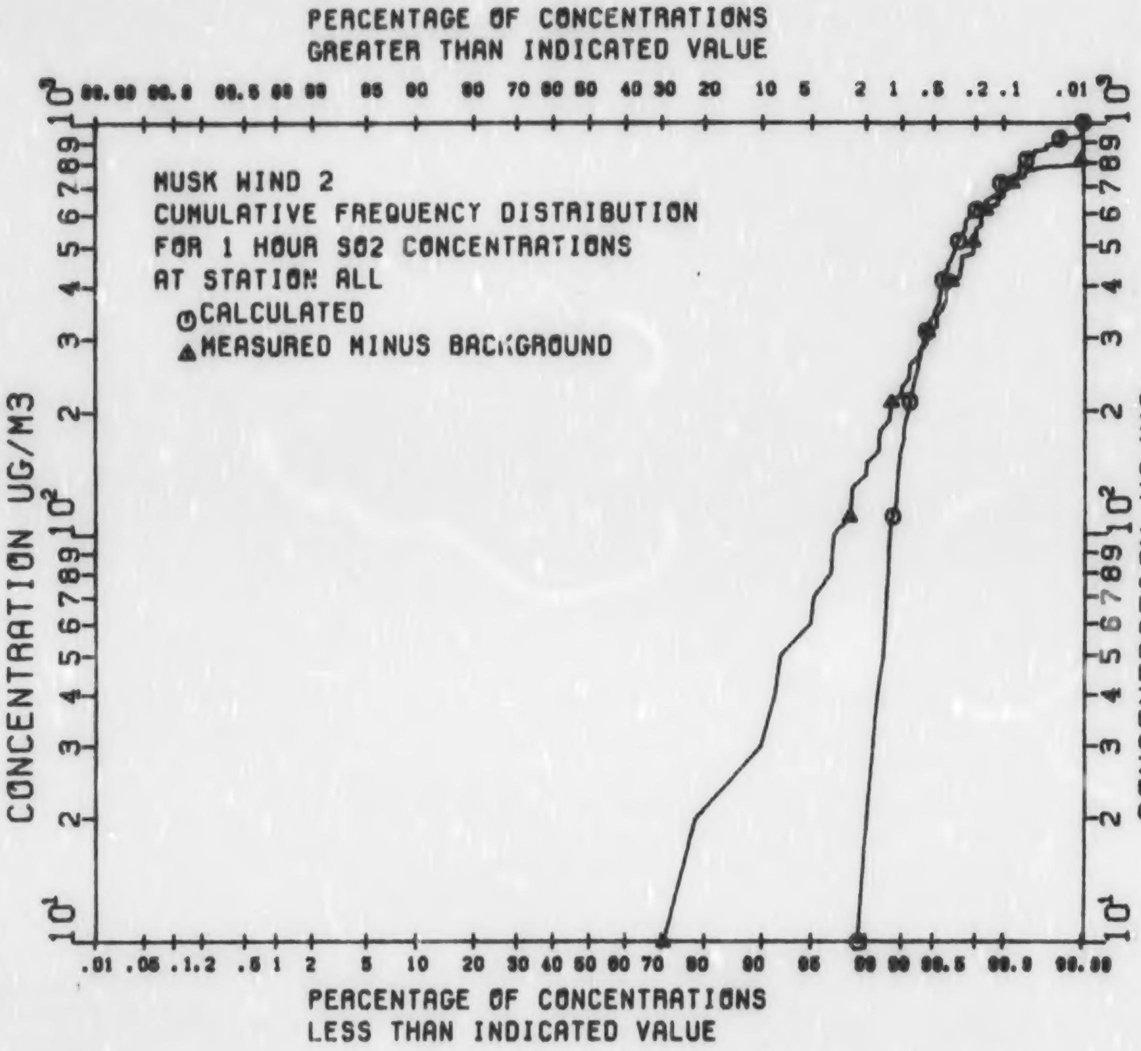

Figure A-4b. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for all receptors for wind speed class 2 (1.6 to 2.4 m/sec)

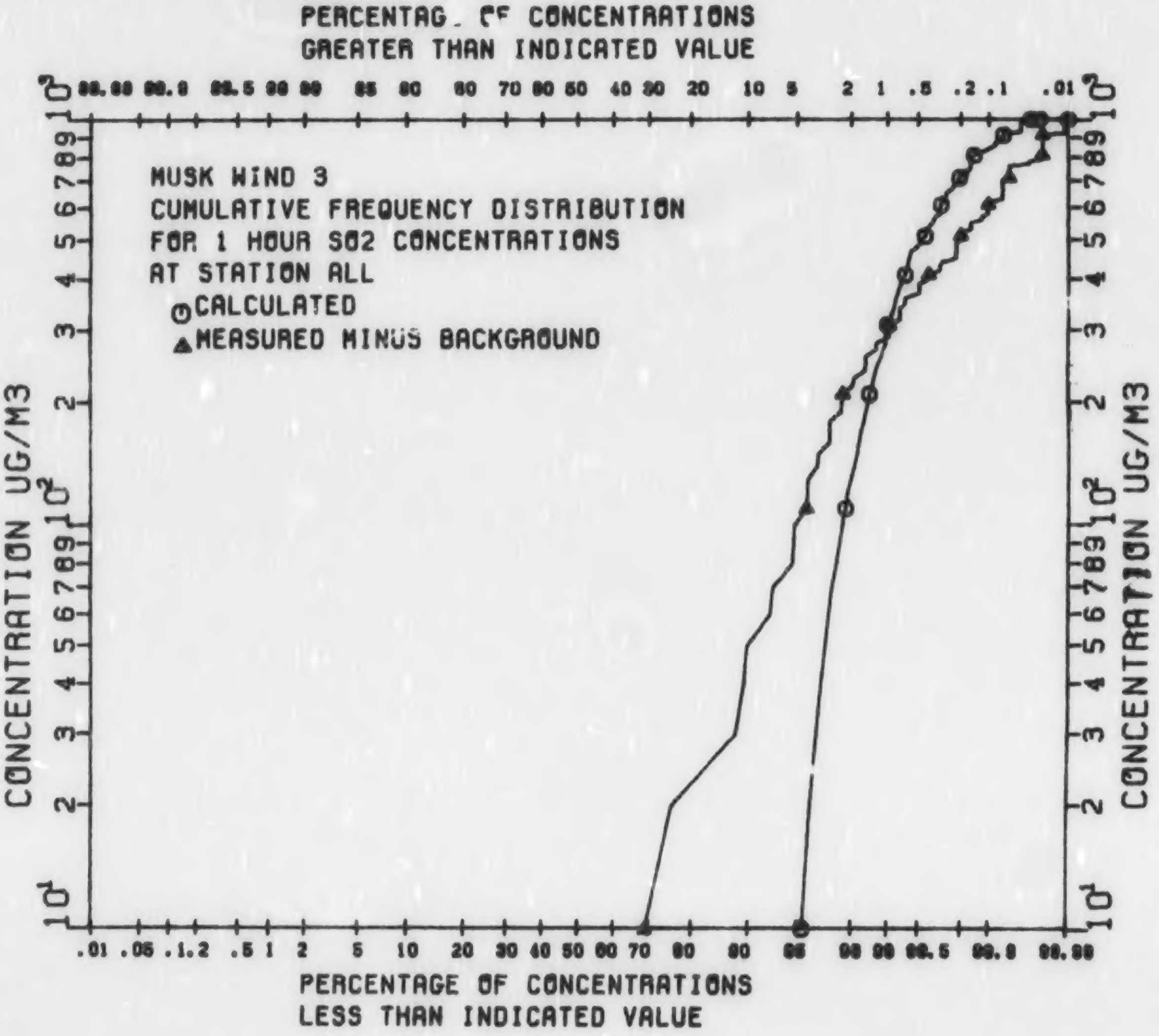

Figure A-4c. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for all receptors for wind speed class 3 (2.4 m/sec)

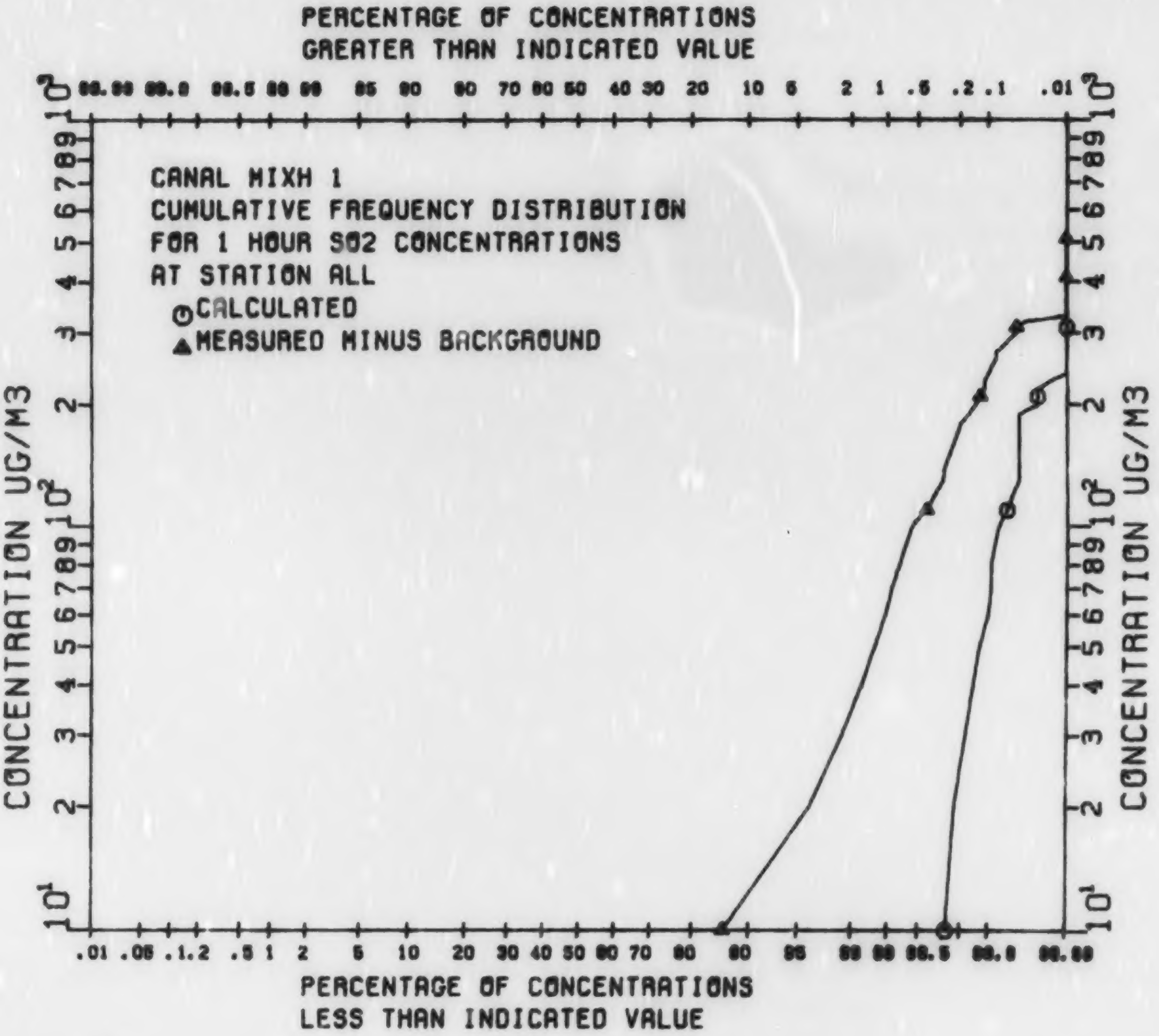

Figure A-5a. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for all receptors for mixing height class 1 (0 to 750 m)

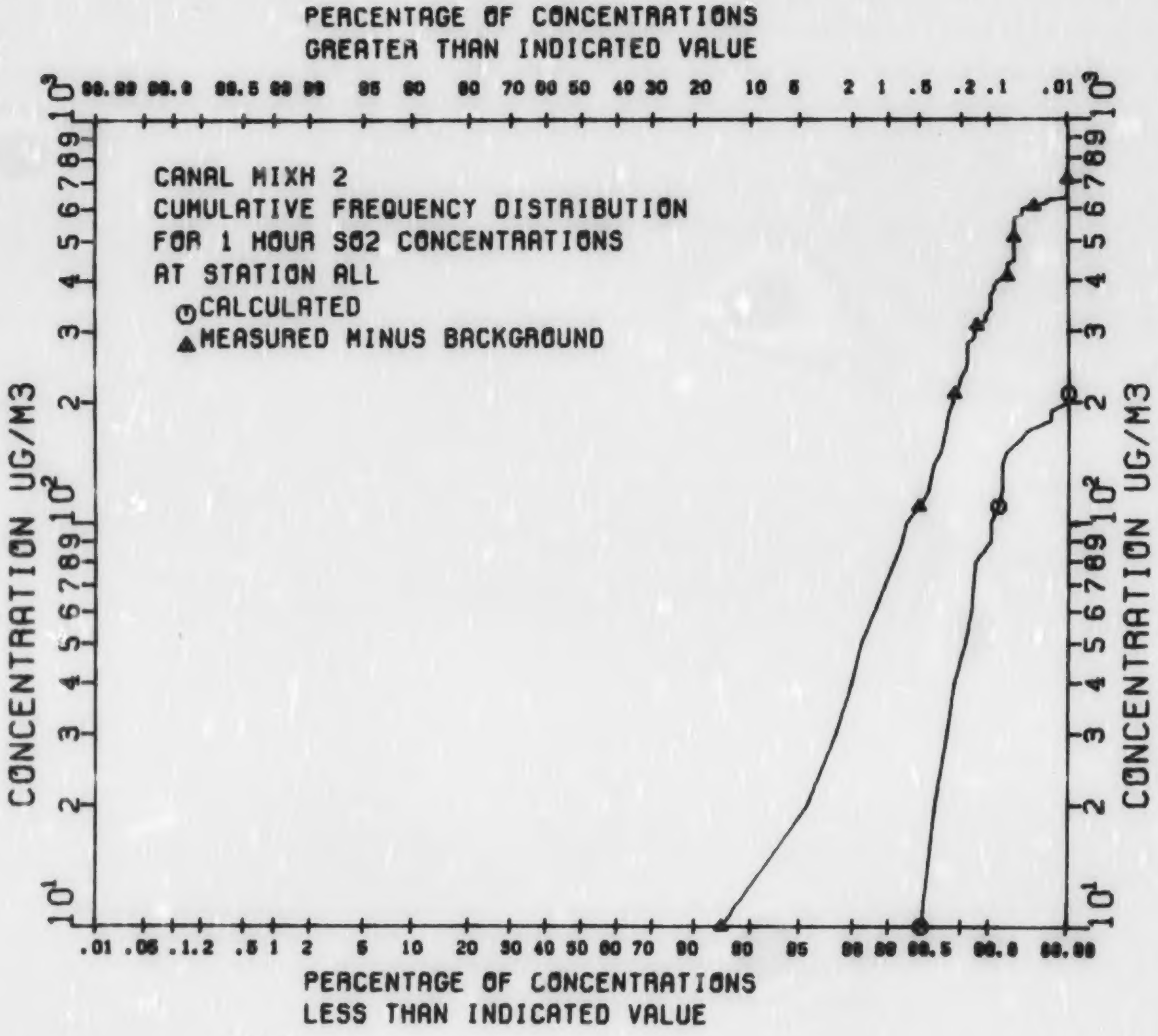

Figure A-5b. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for all receptors for mixing height class 2 (750 to 1250 m)

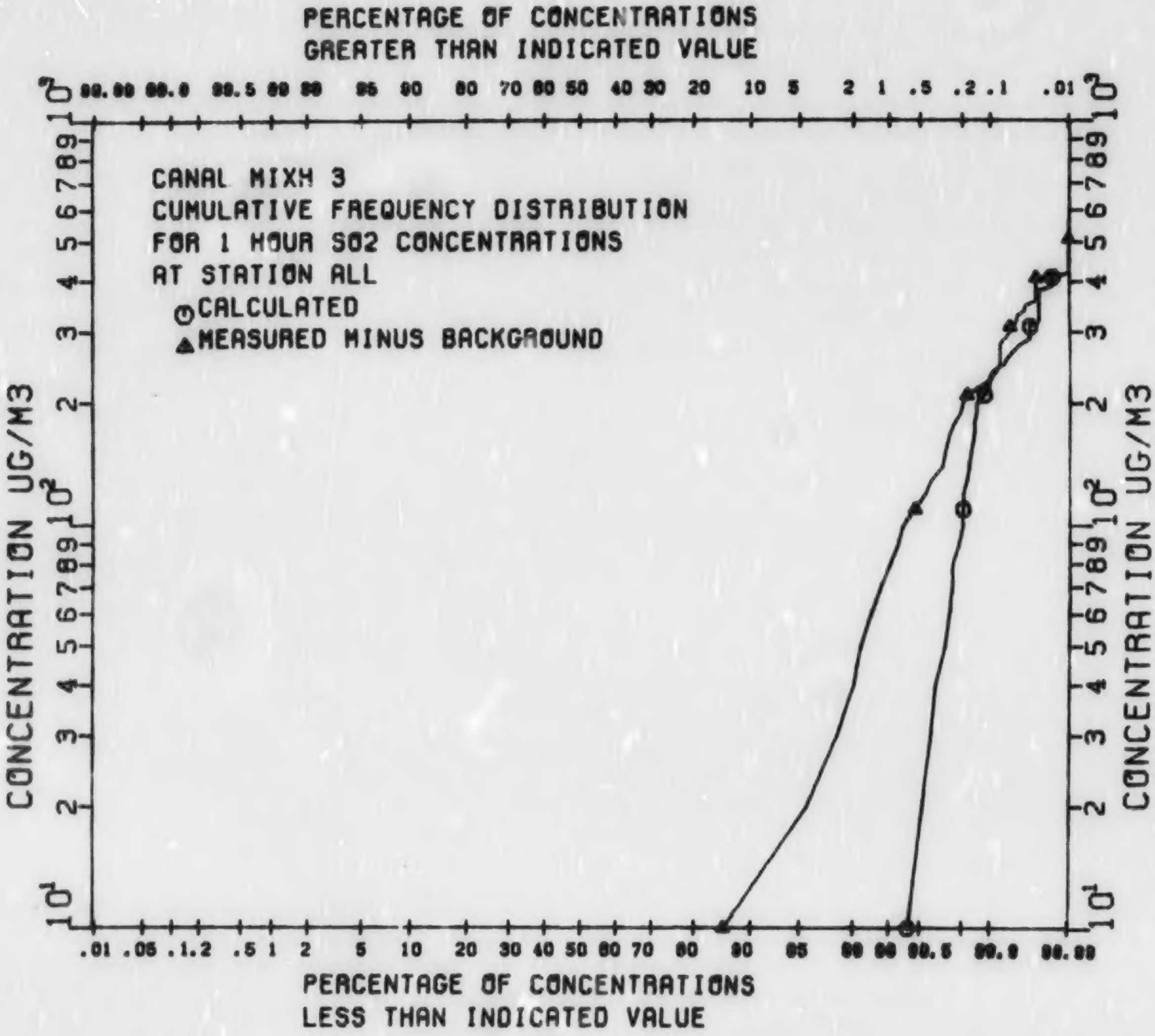

Figure A-5c. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for all receptors for mixing height class 3 (1250 m →)

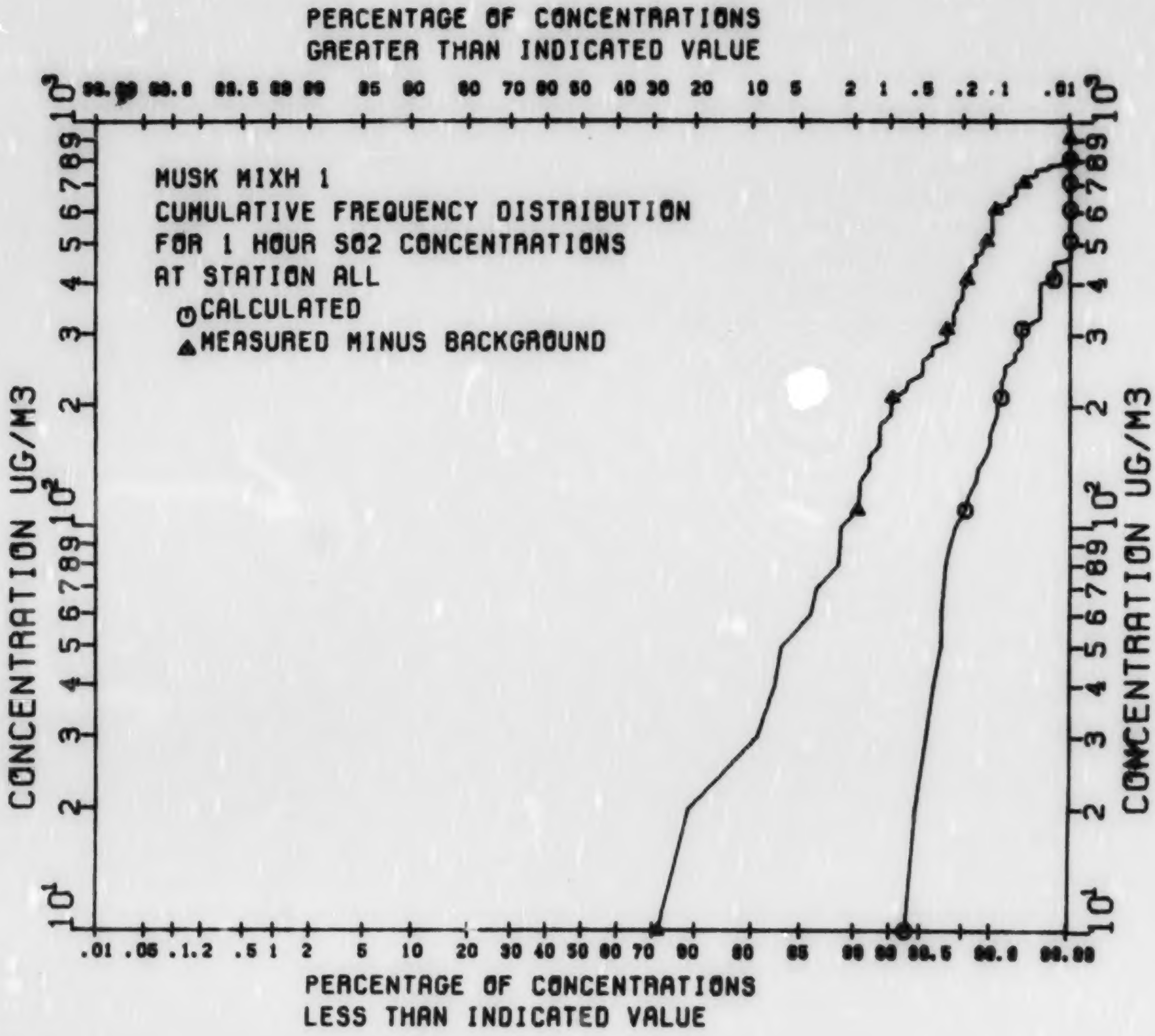

Figure A-6a. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for all receptors for mixing height class 1 (0 to 800 m)

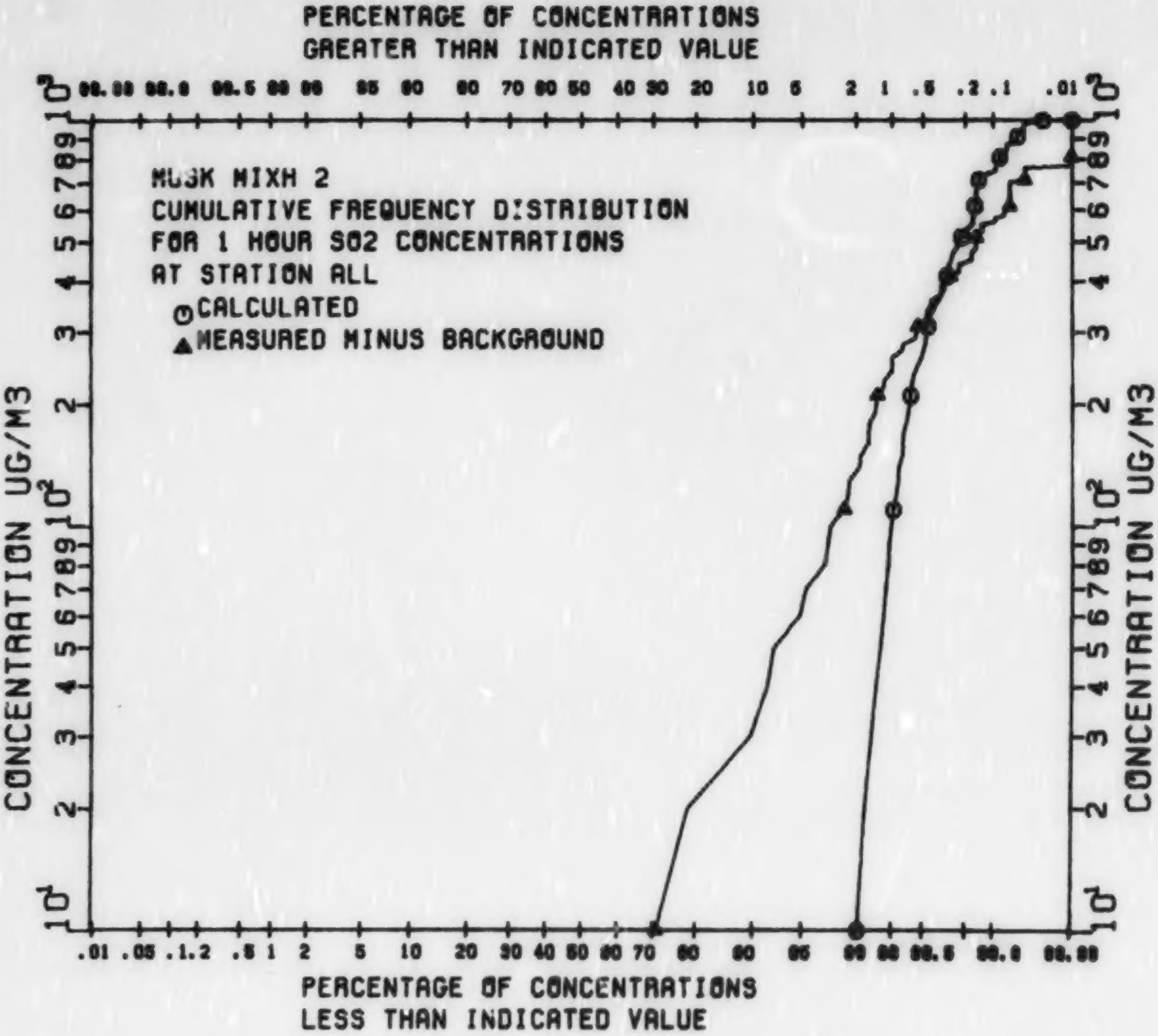

Figure A-6b. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for all receptors for mixing height class 2 (800 to 1200 m)

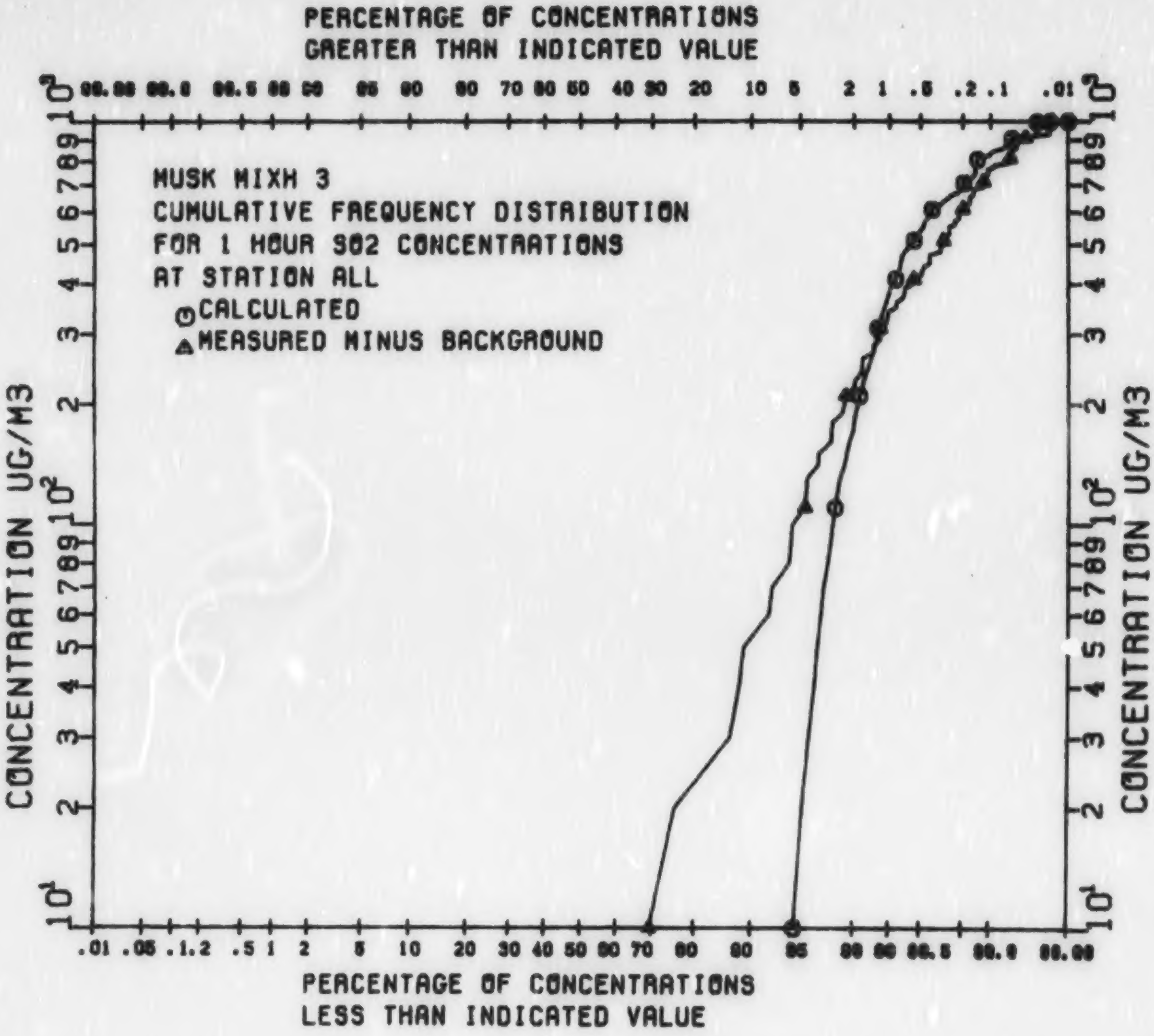

Figure A-6c. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for all receptors for mixing height class 3 (1200 m →)

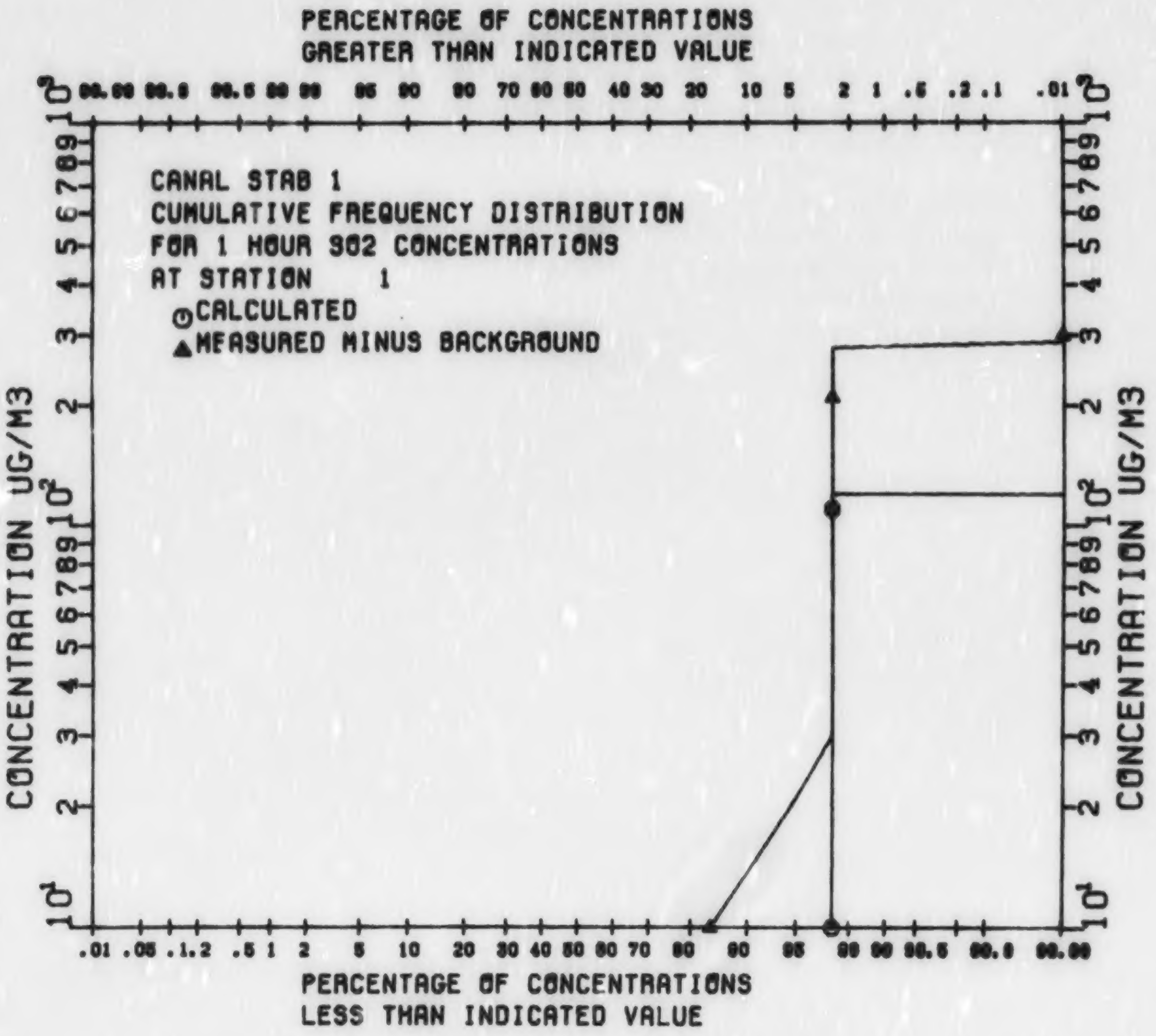

Figure A-7a. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 1 for stability A

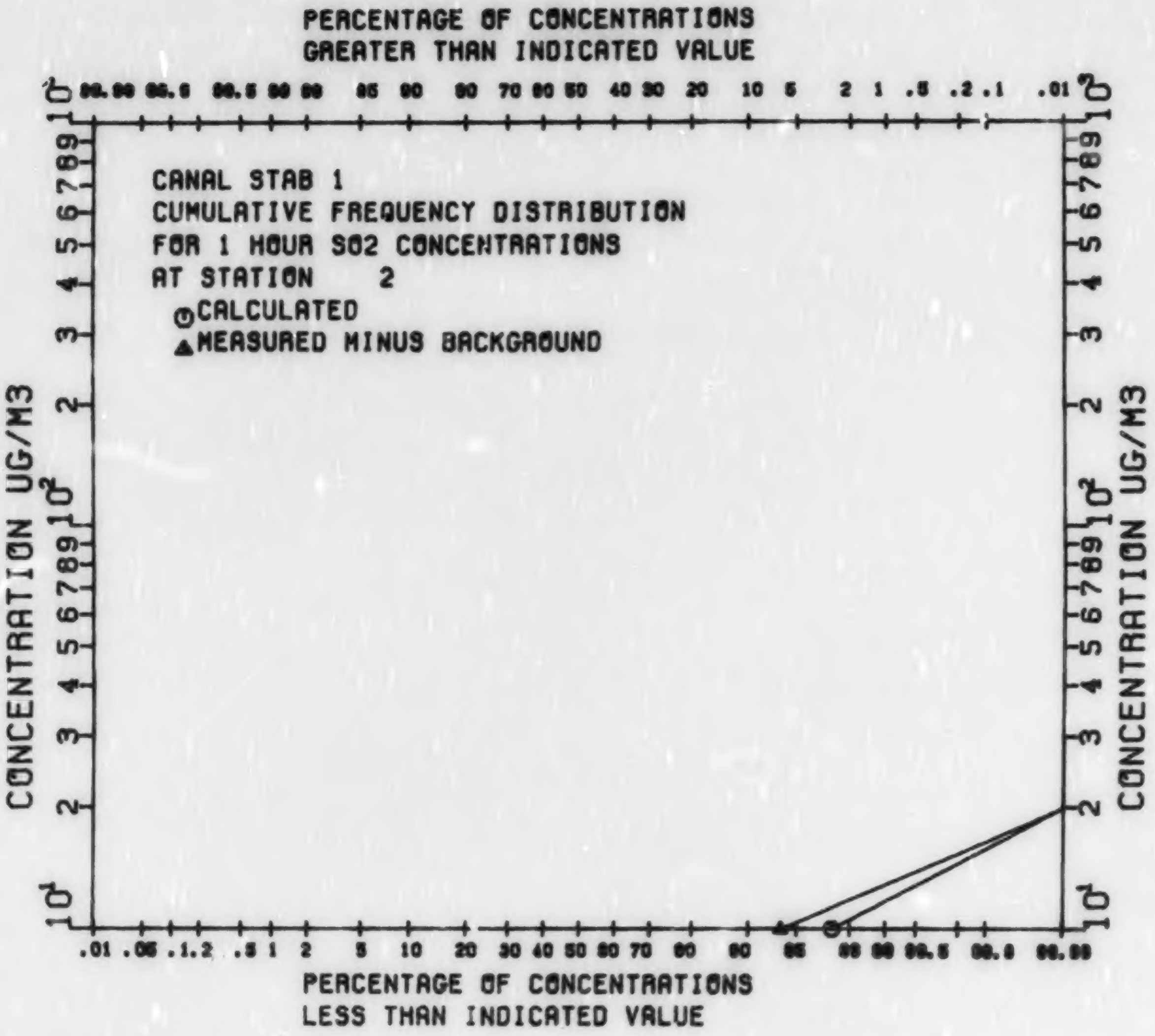

Figure A-7b. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 2 for stability A

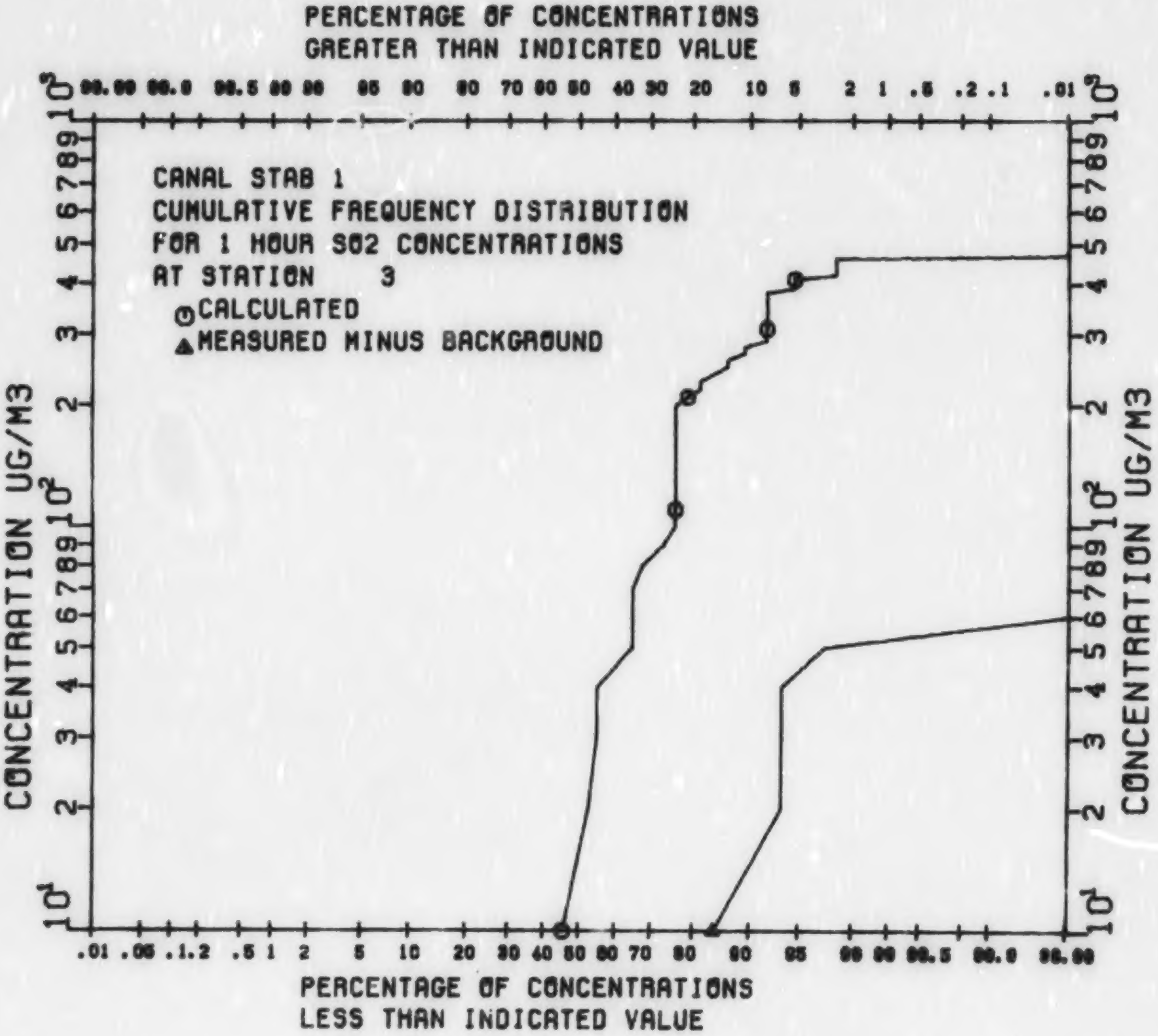

Figure A-7c. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 3 for stability A

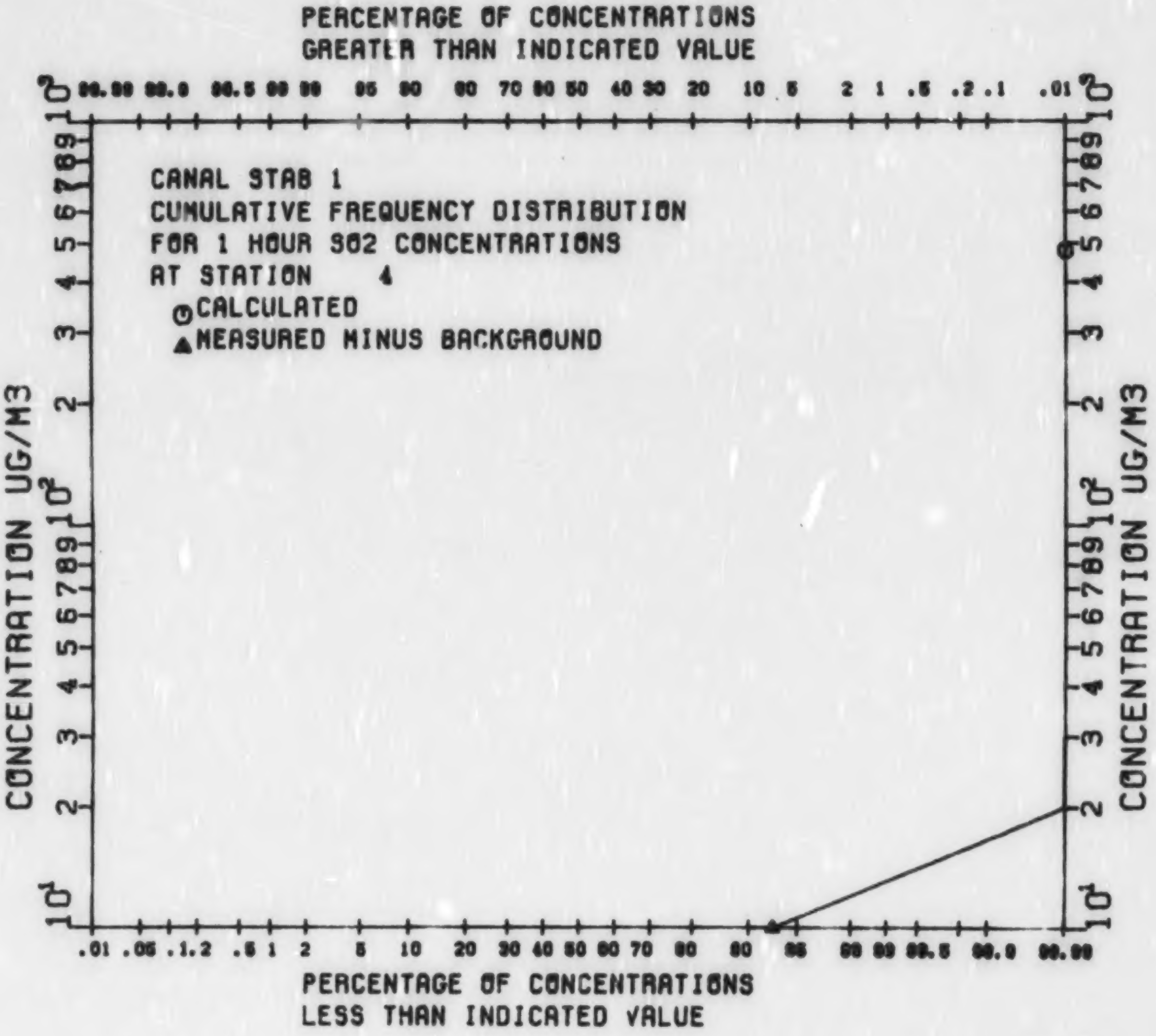

Figure A-7d. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 4 for stability A

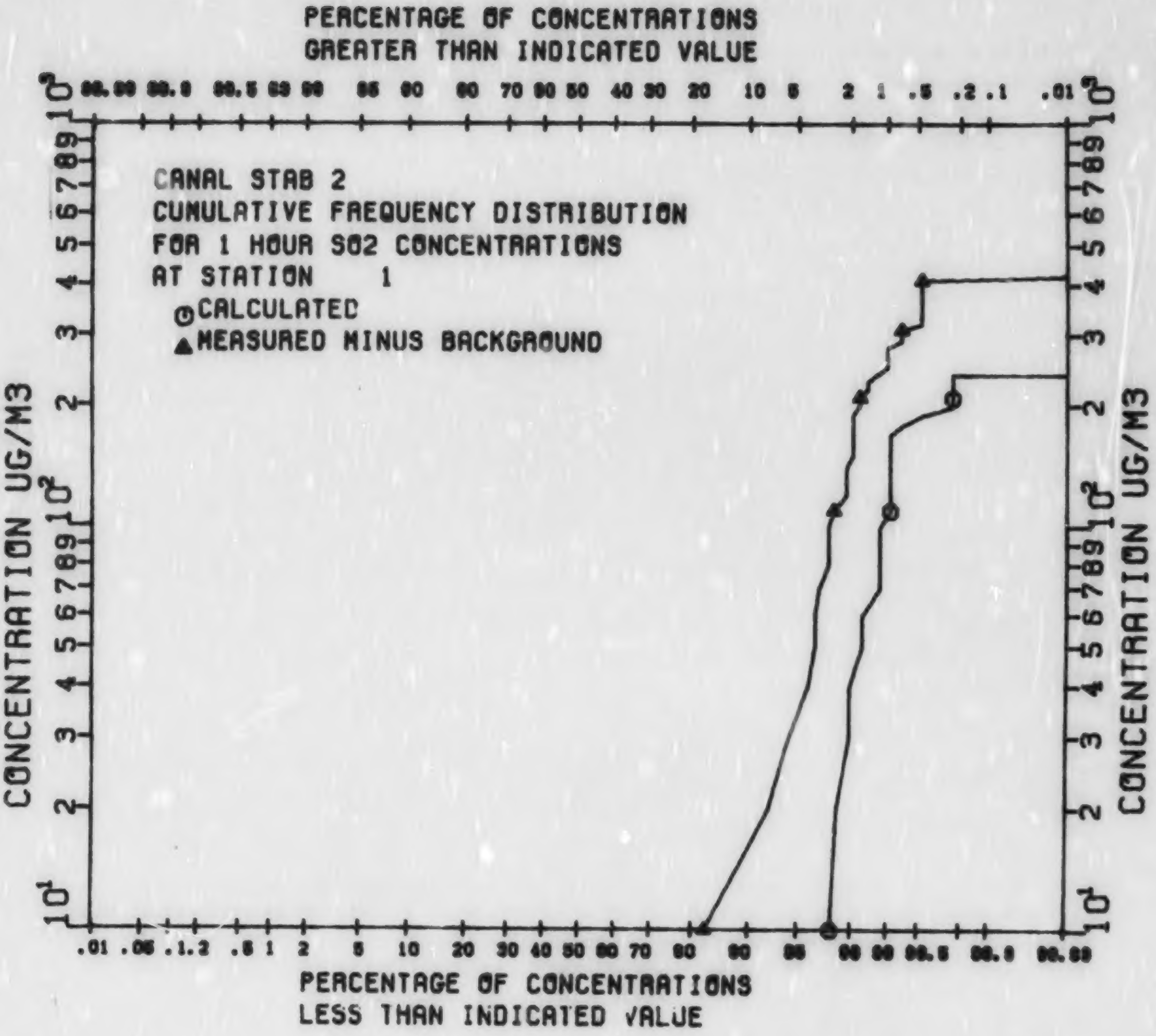

Figure A-8a. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 1 for stability B

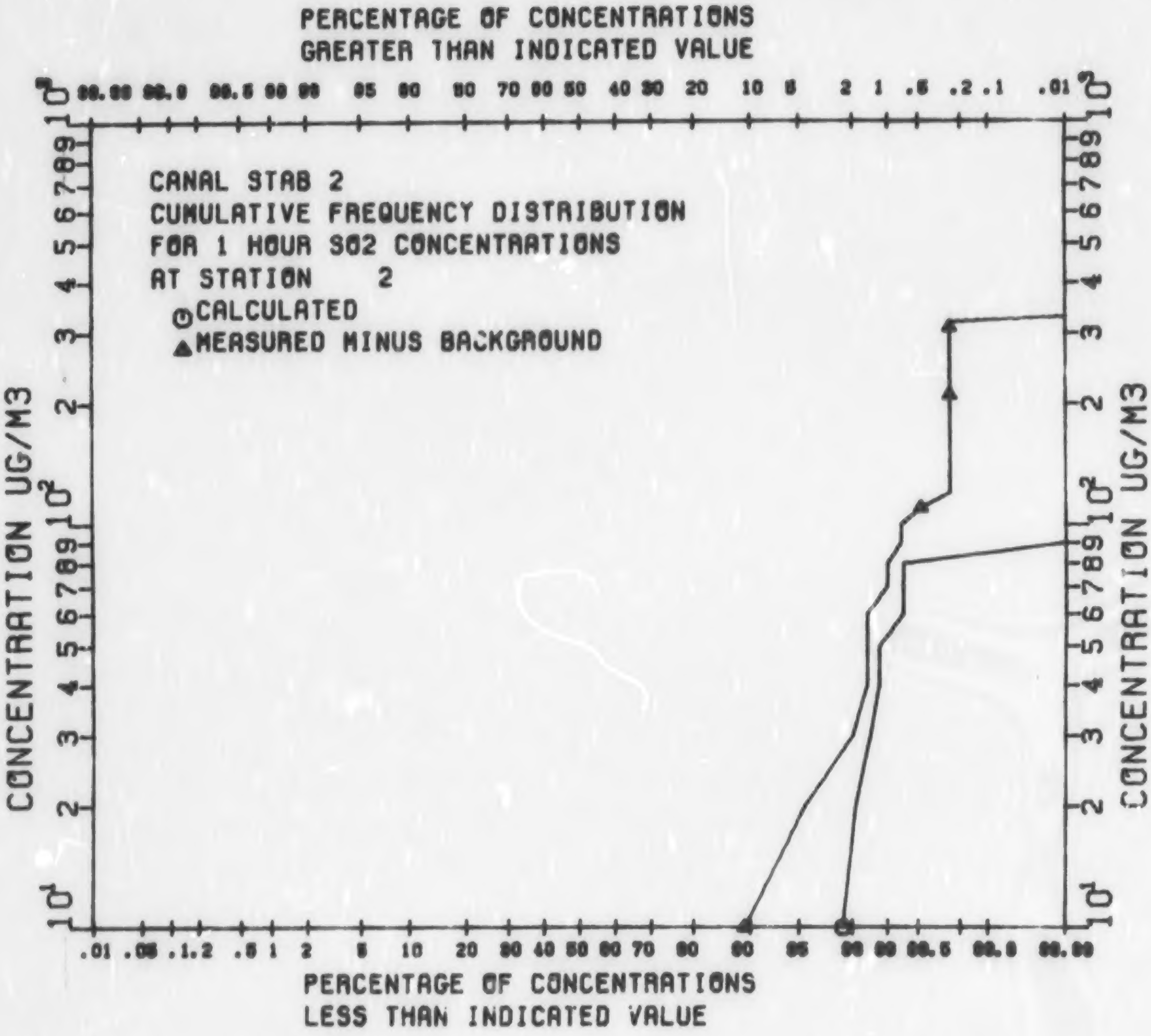

Figure A-8b. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 2 for stability B

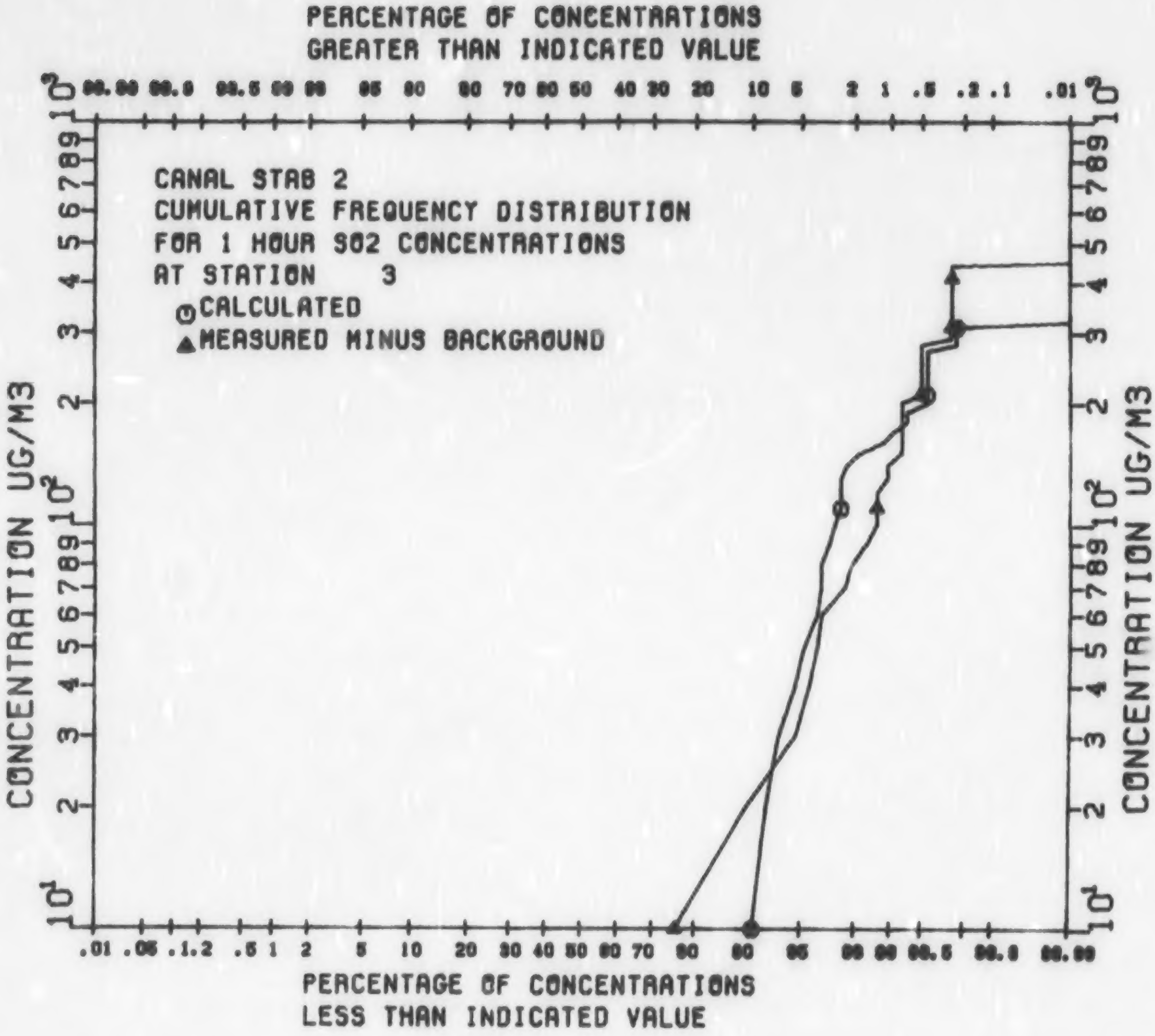

Figure A-8c. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 3 for stability B

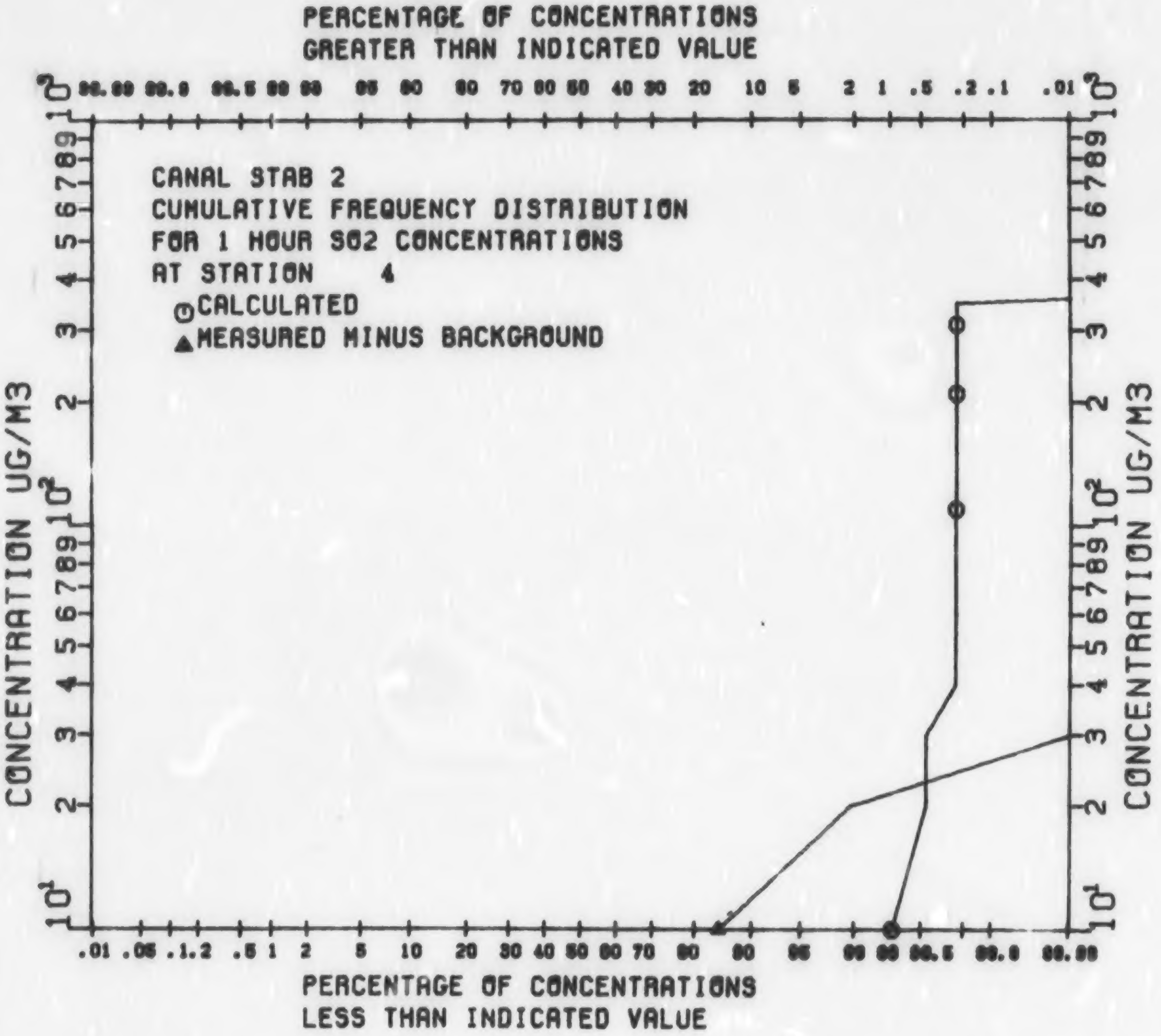

Figure A-8d. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 4 for stability B

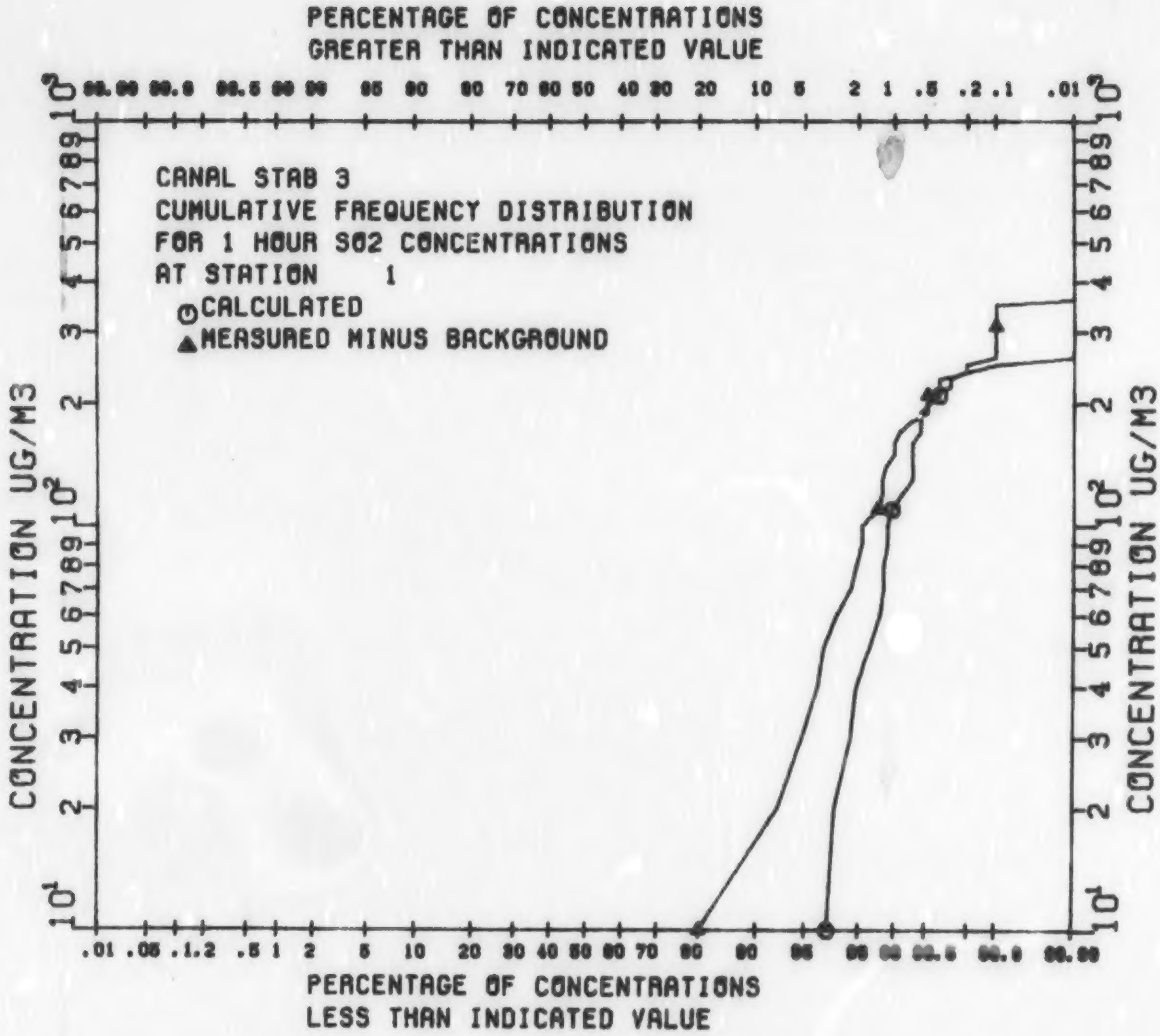

Figure A-9a. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 1 for stability C

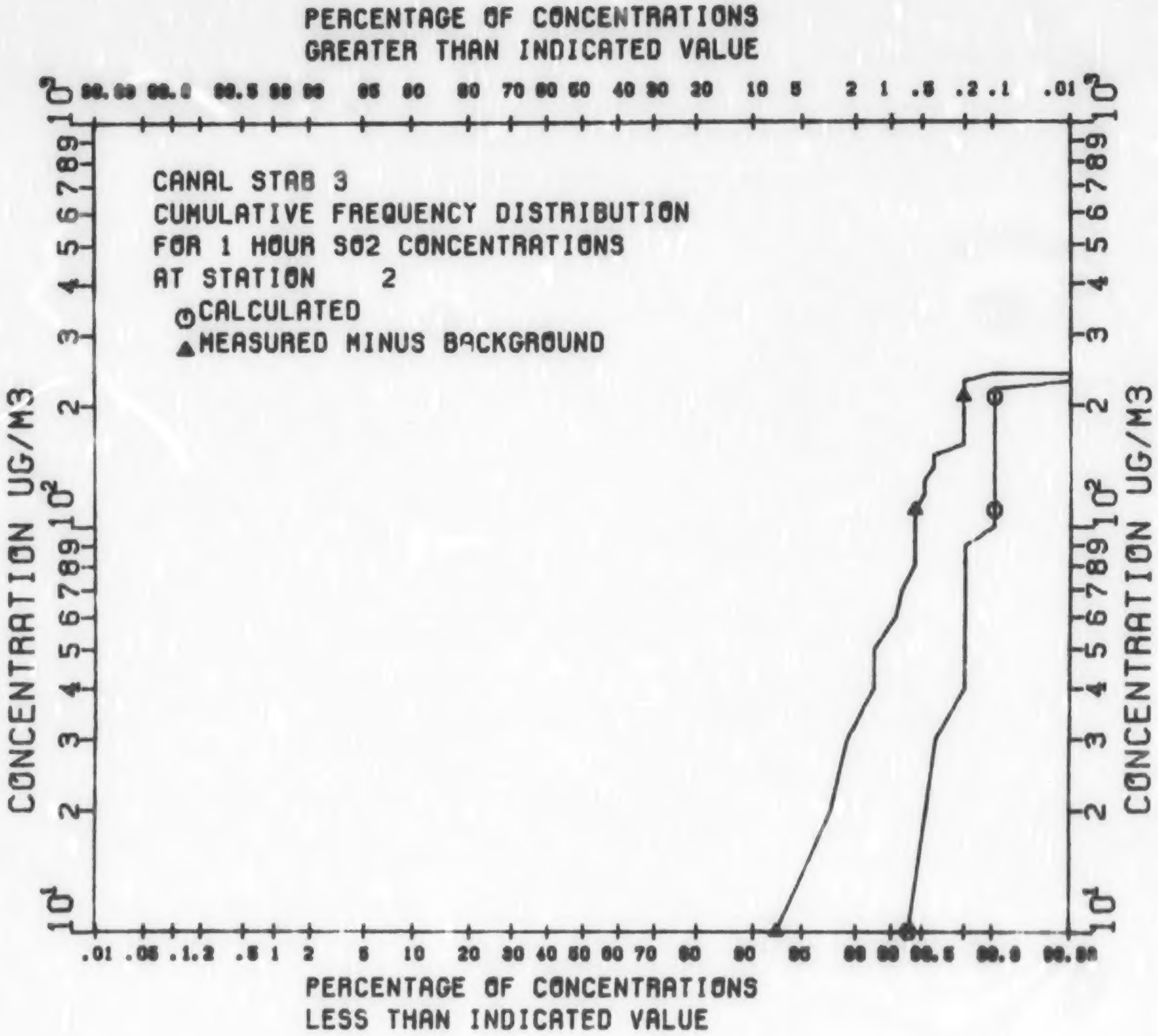

Figure A-9b. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 2 for stability C

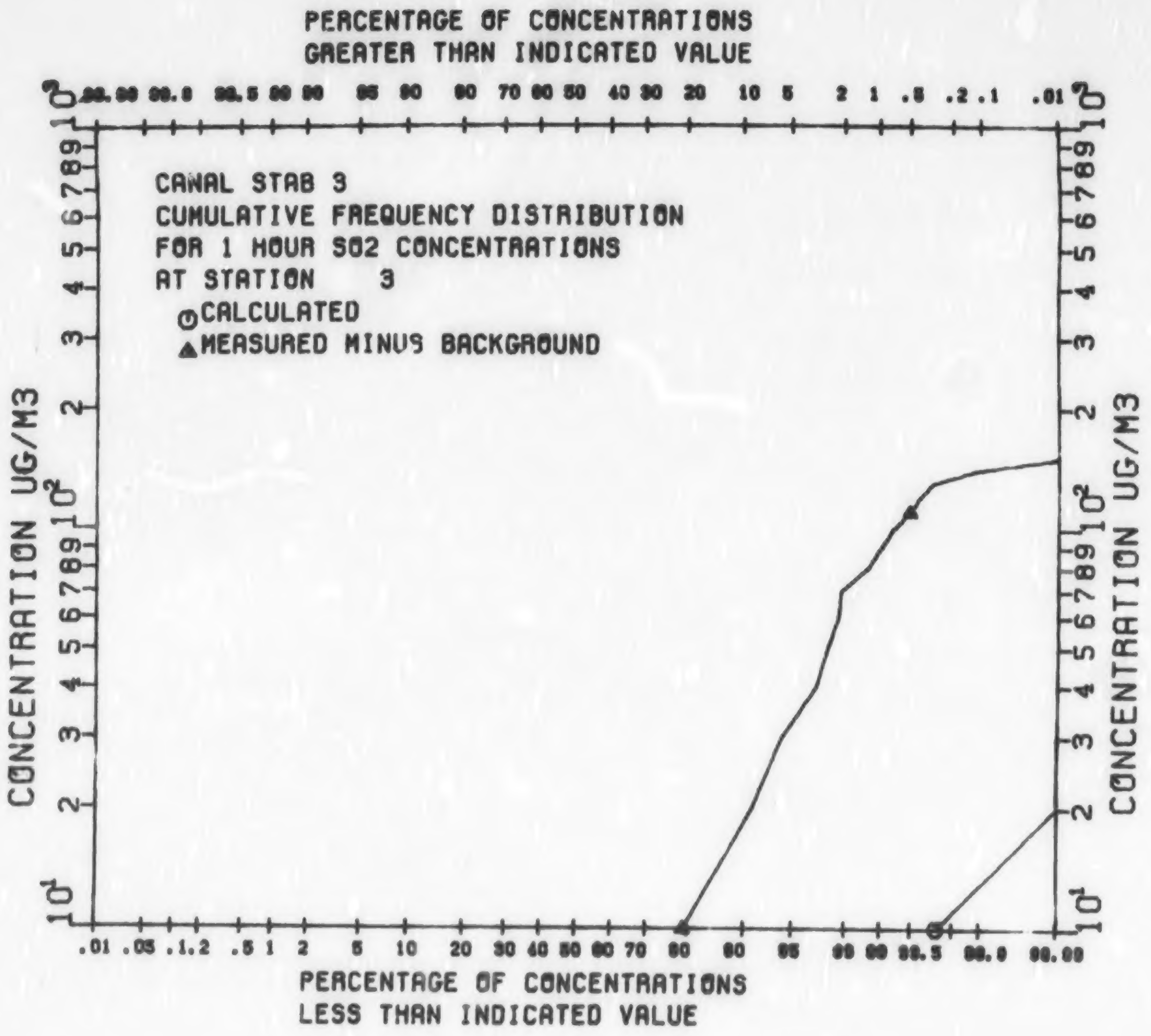

Figure A-9c. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 3 for stability C

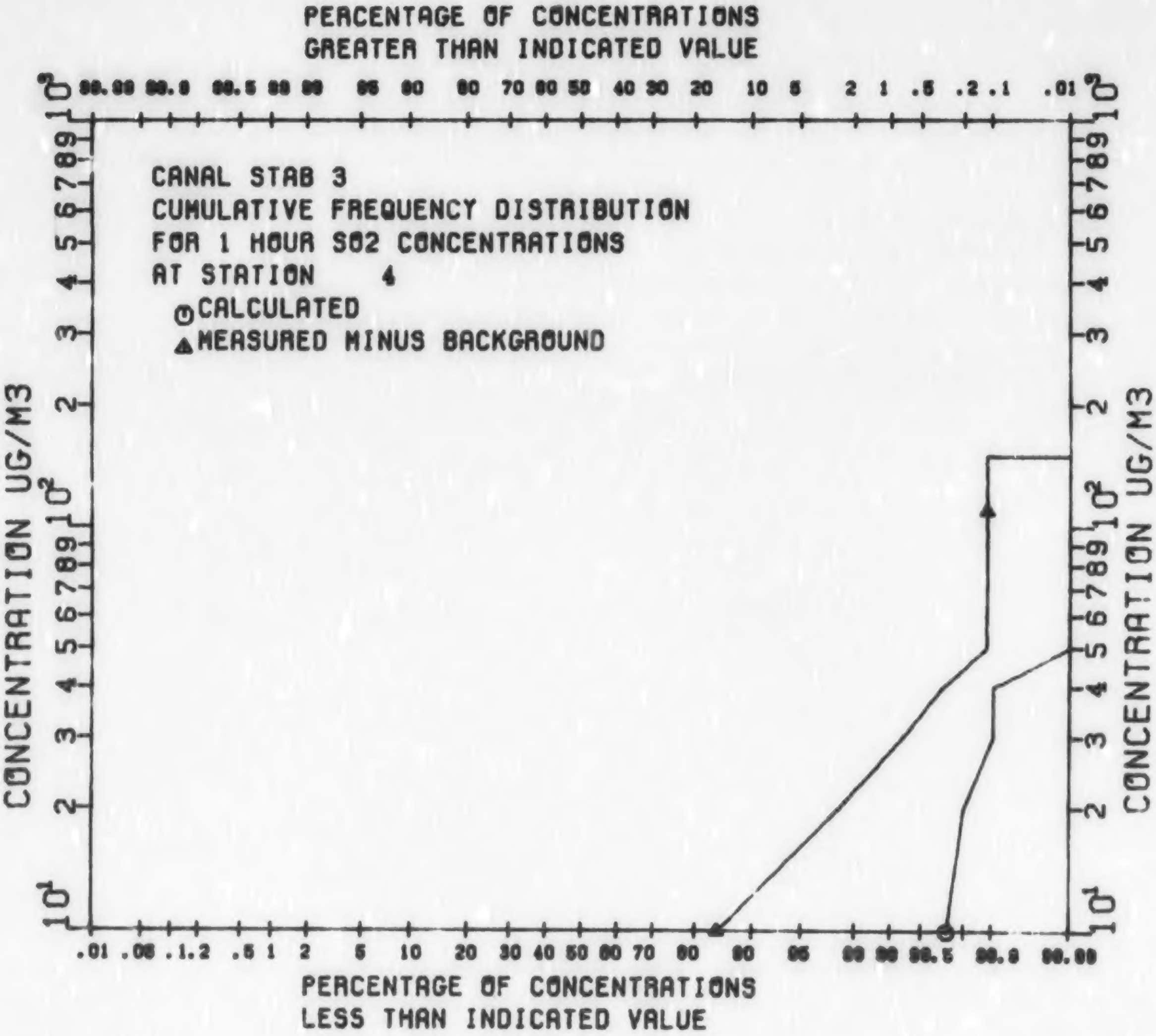

Figure A-9d. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 4 for stability C

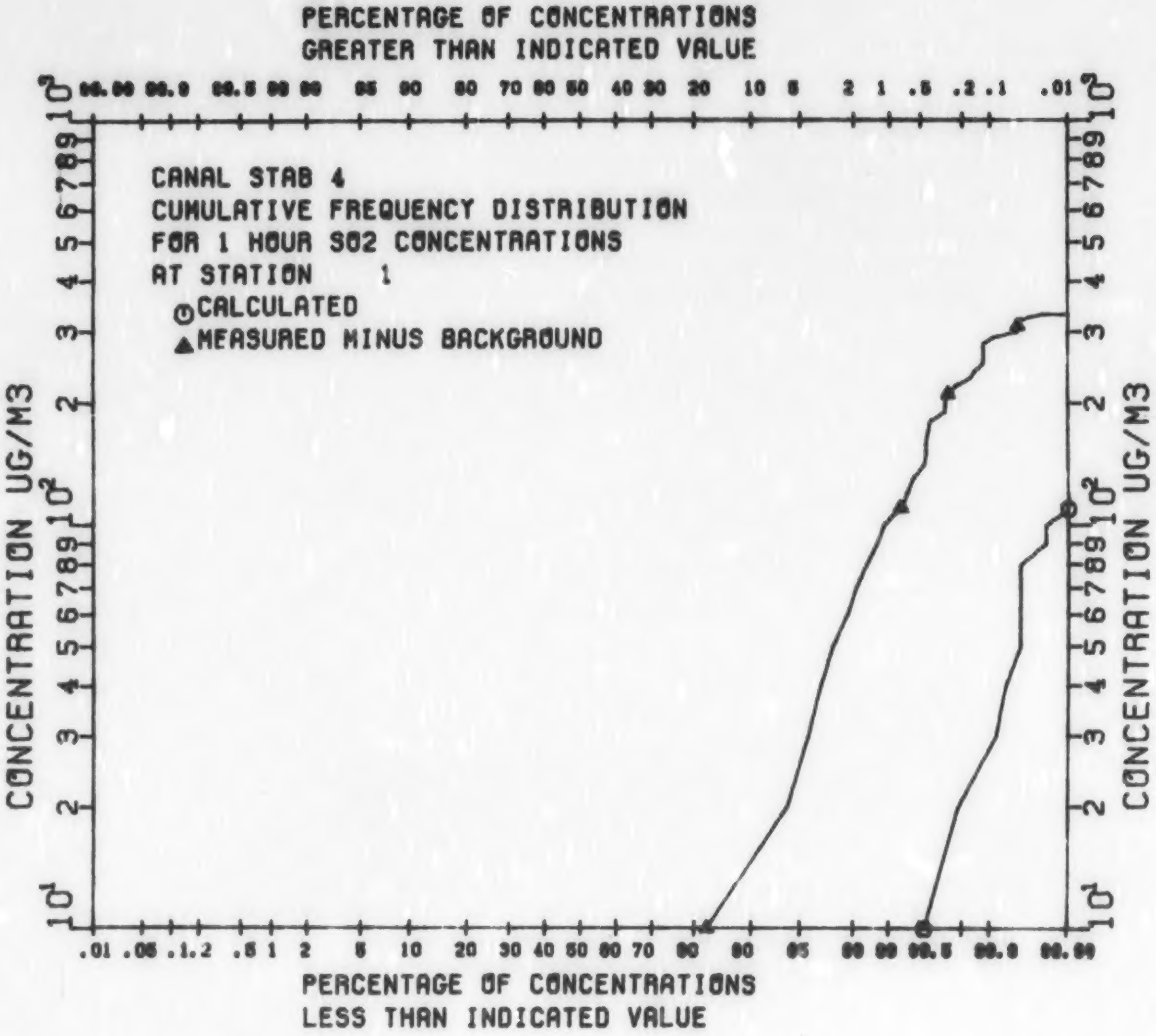

Figure A-10a. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 1 for stability D

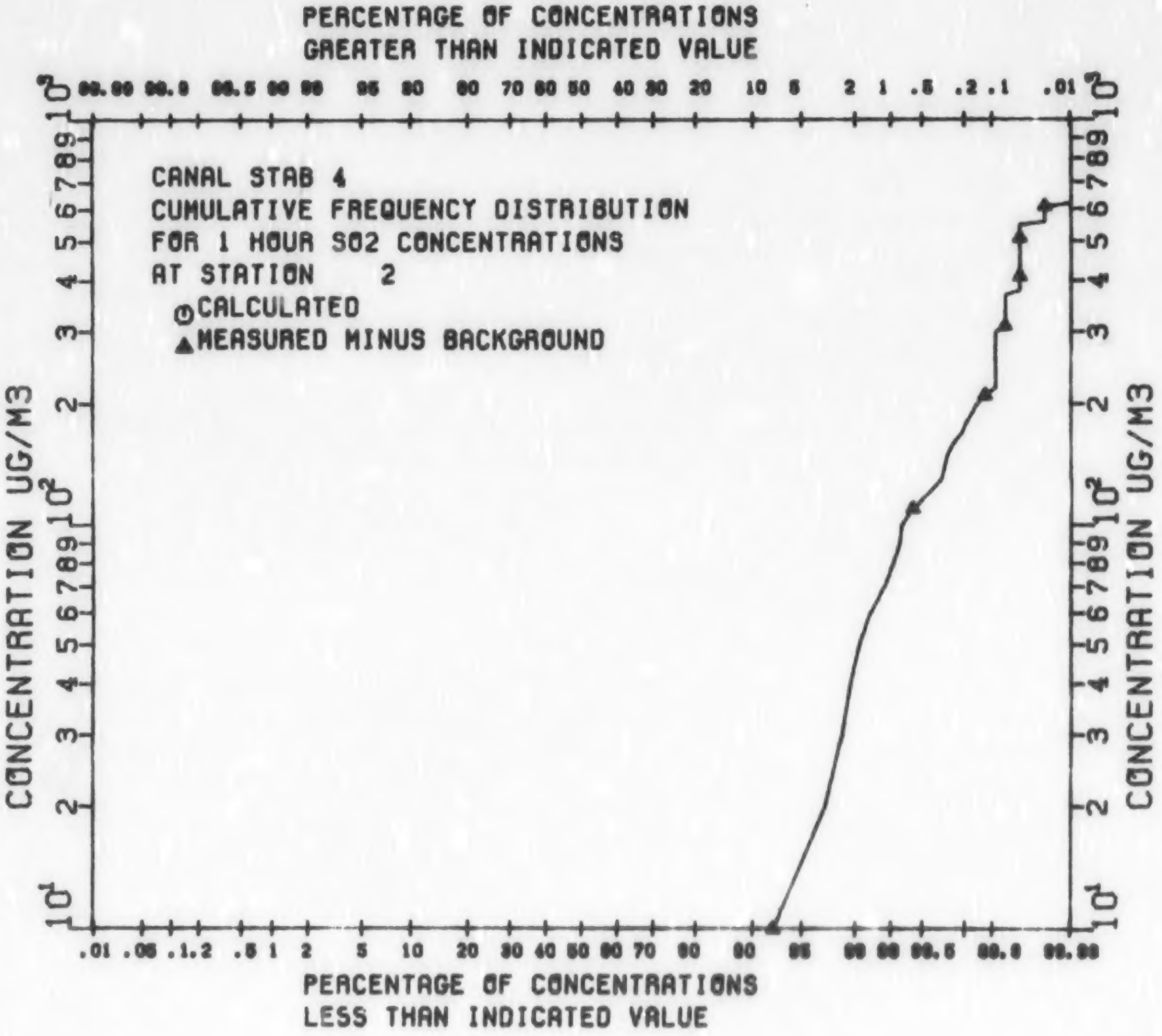

Figure A-10b. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 2 for stability D

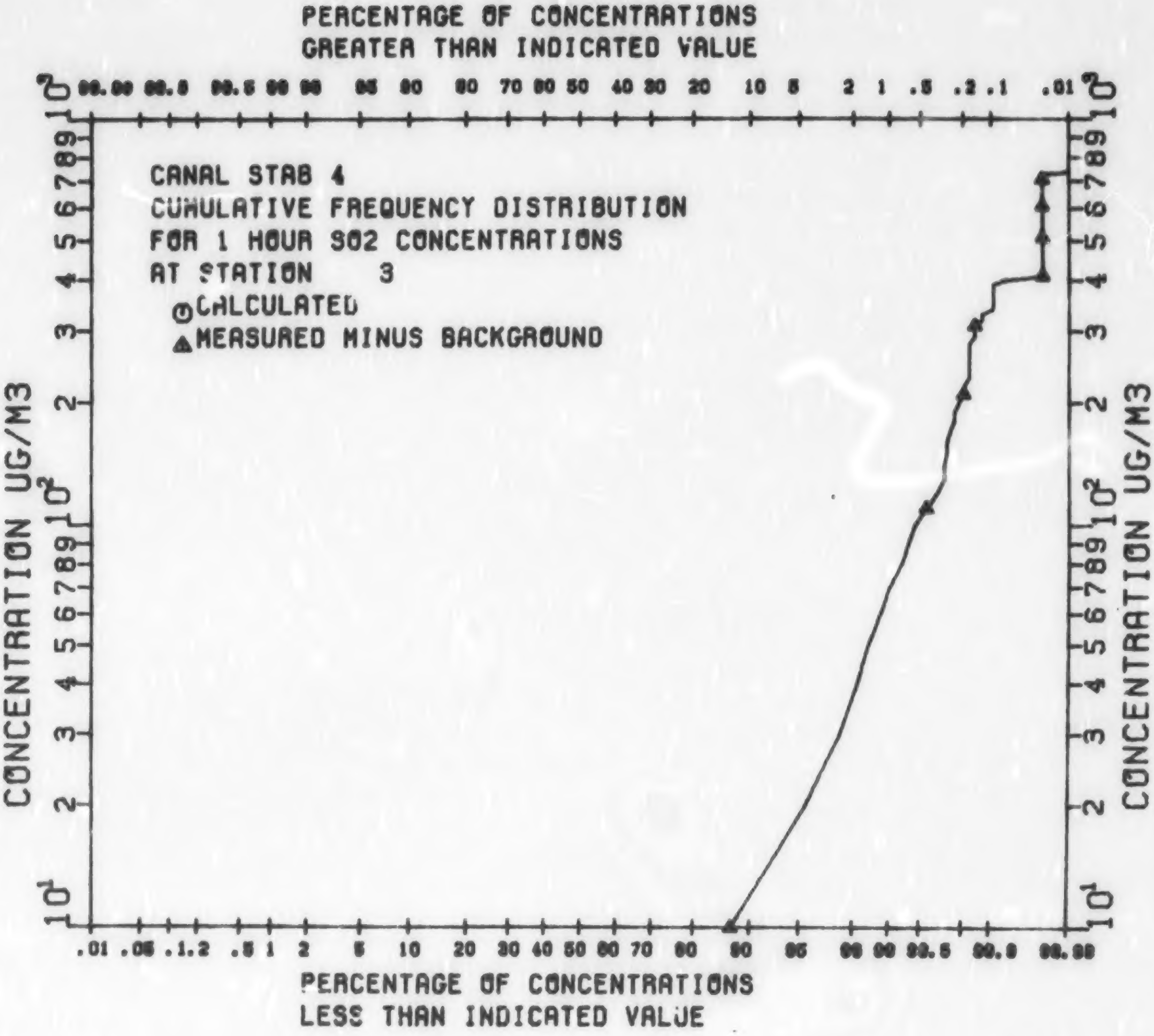

Figure A-10c. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 3 for stability D

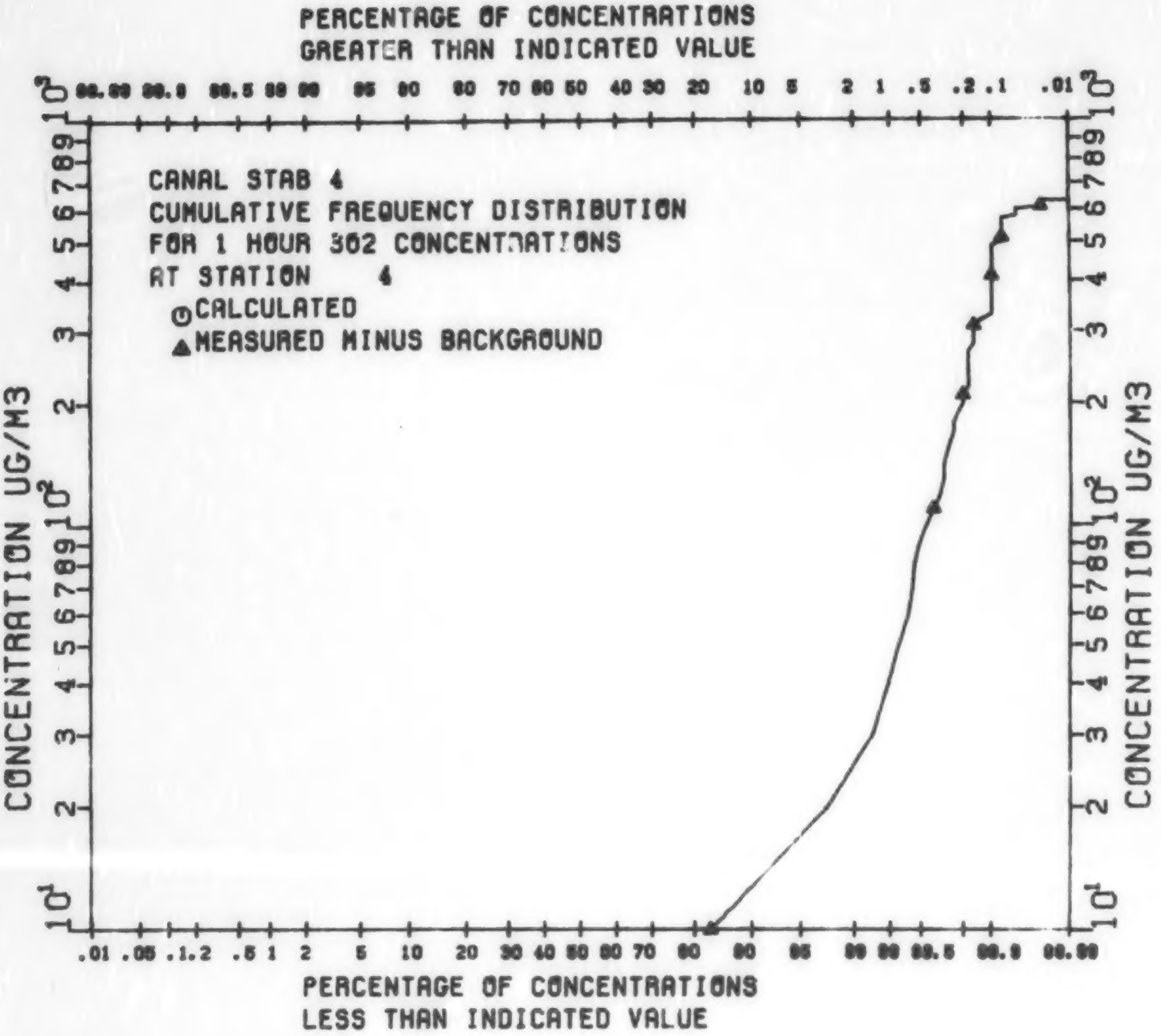

Figure A-10d. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 4 for stability D

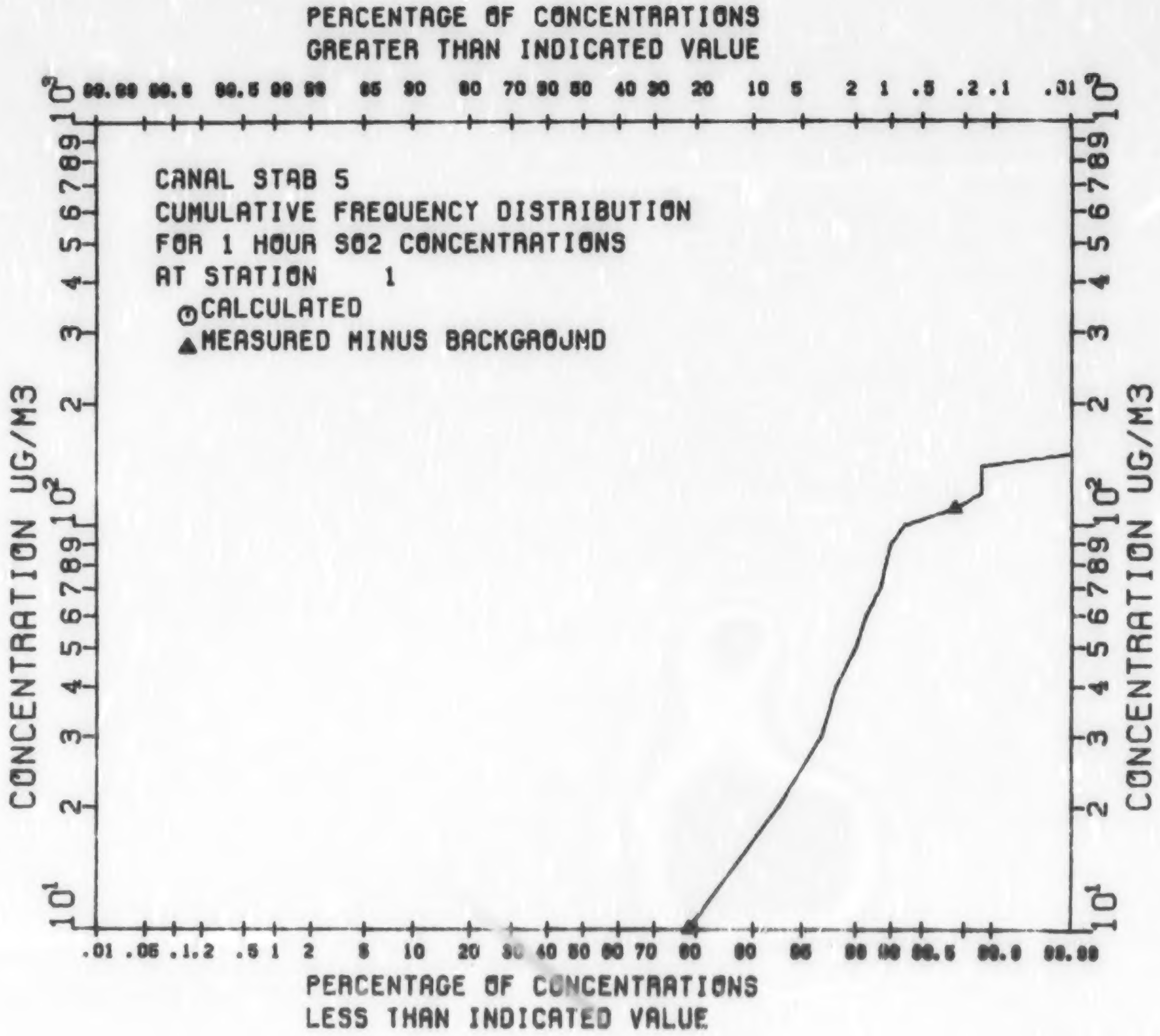

Figure A-11a. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 1 for stability E

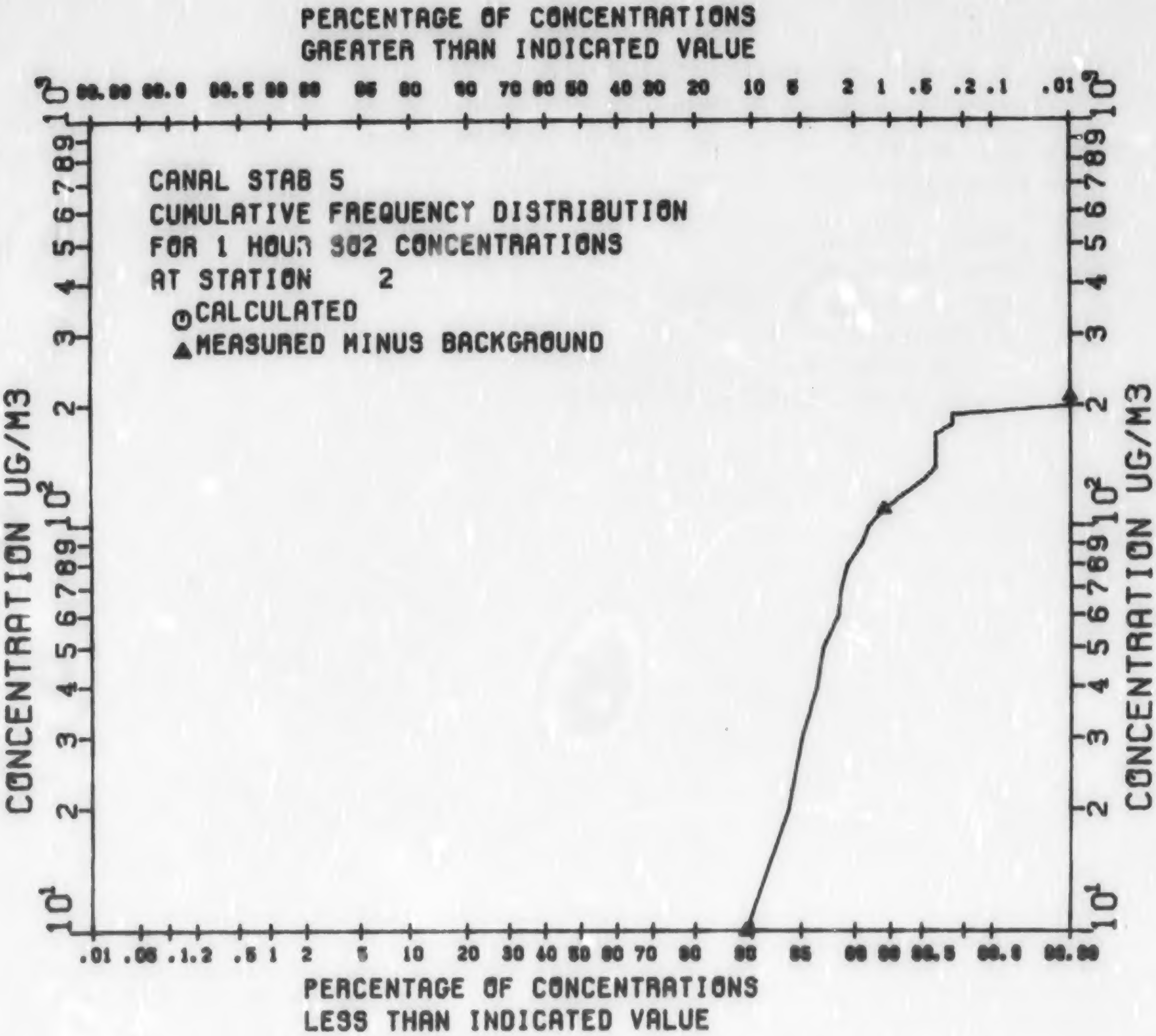

Figure A-11b. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 2 for stability E

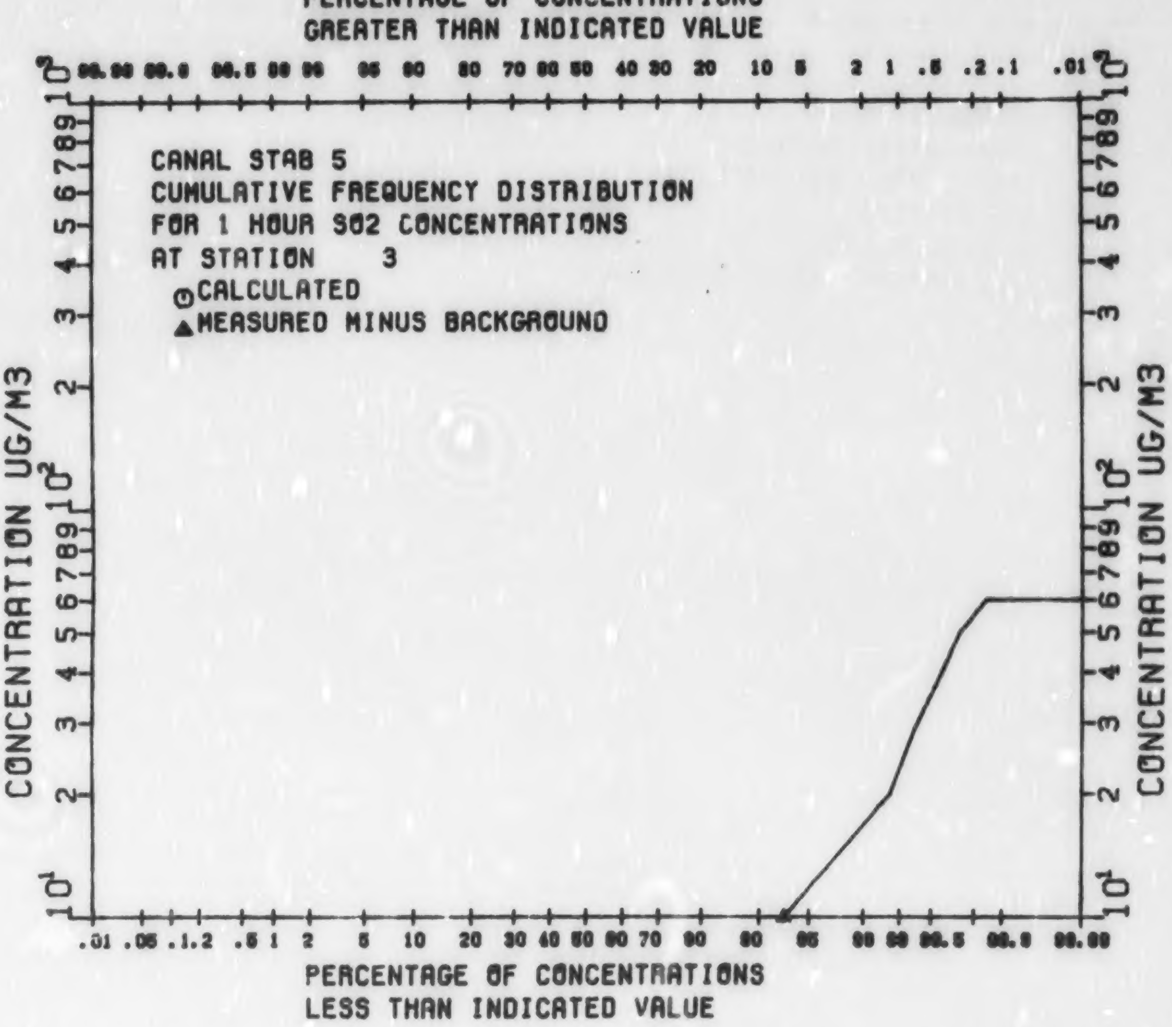

Figure A-11c. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 3 for stability E

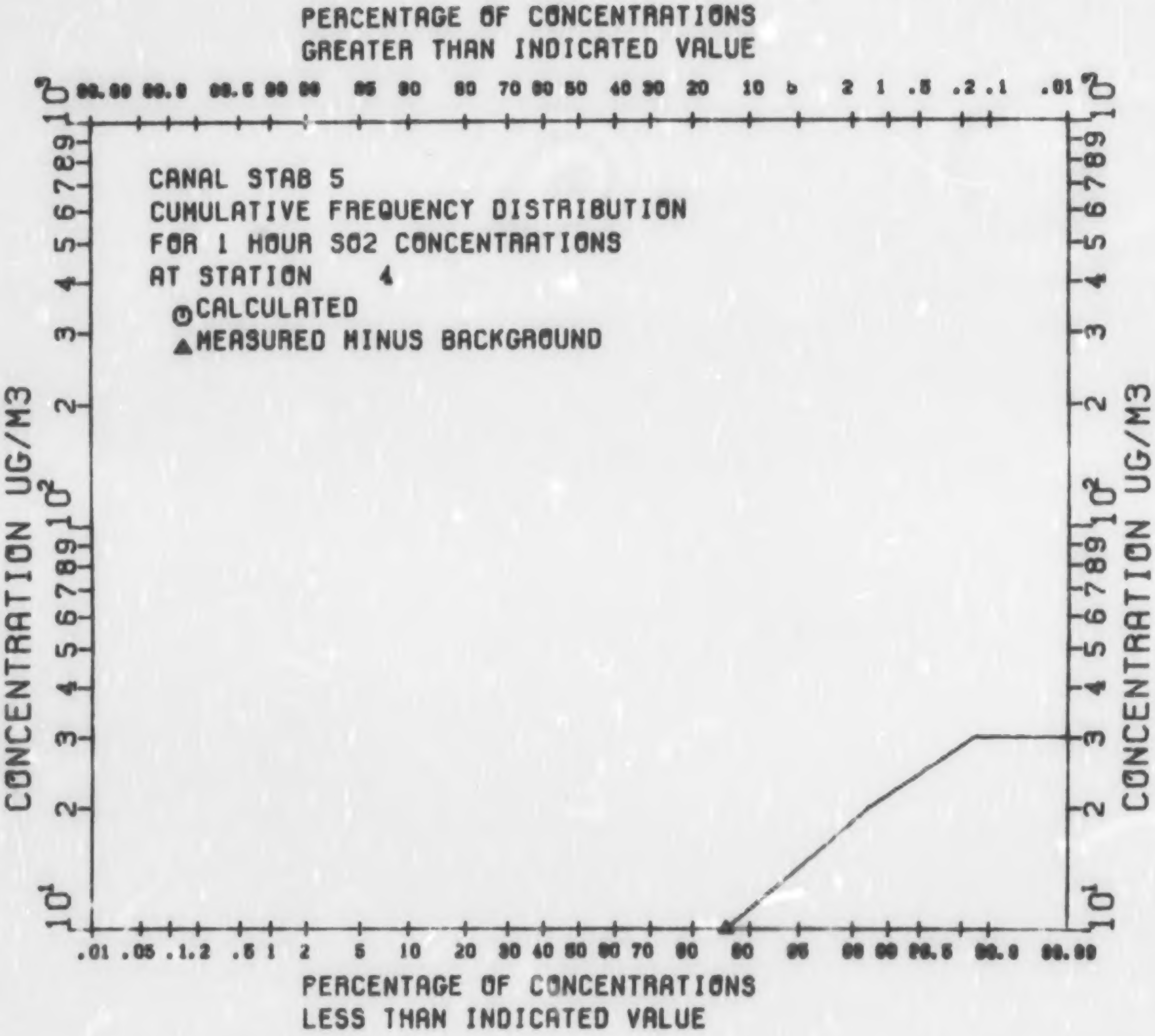

Figure A-11d. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 4 for stability E

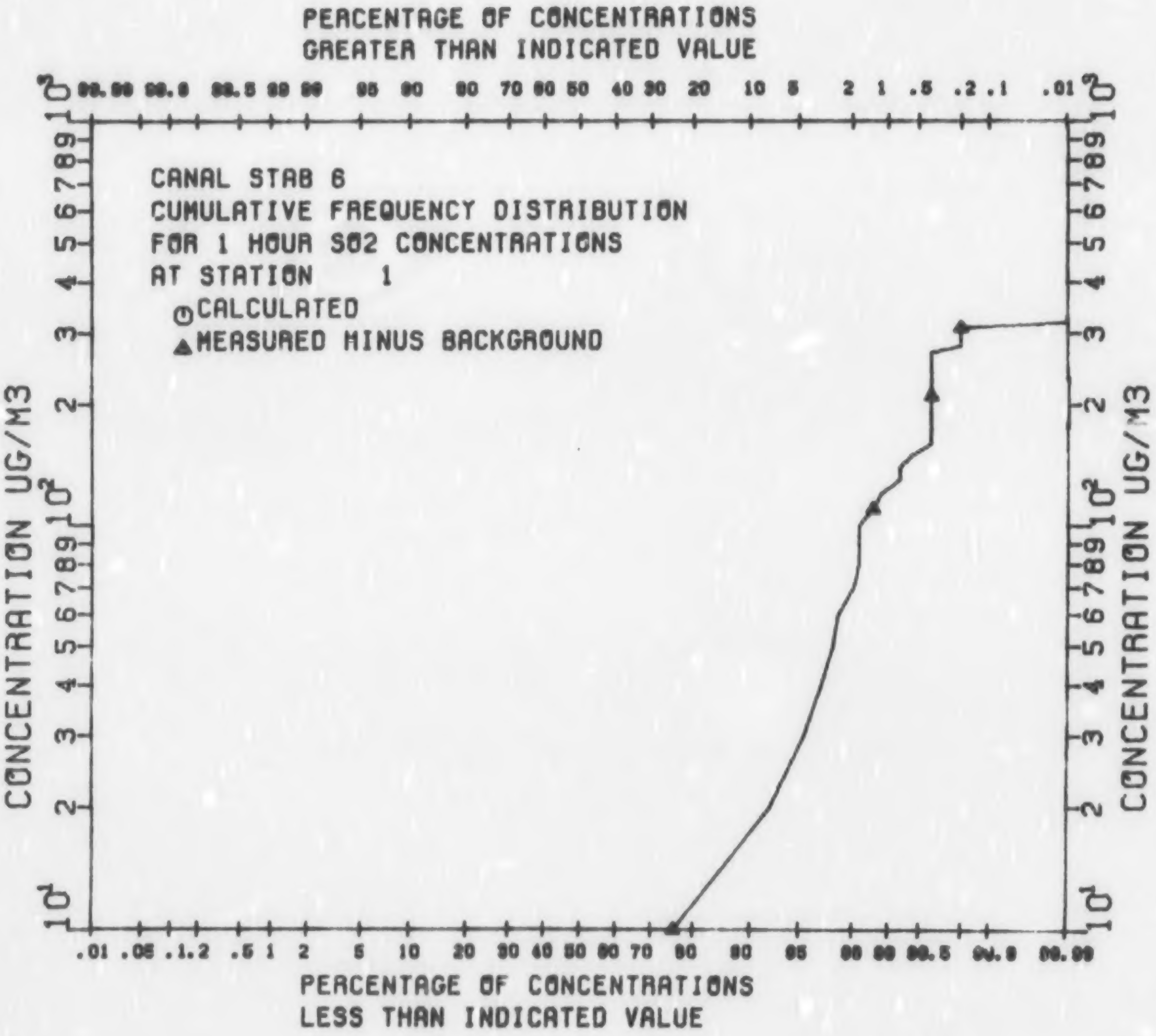

Figure A-12a. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 1 for stability F

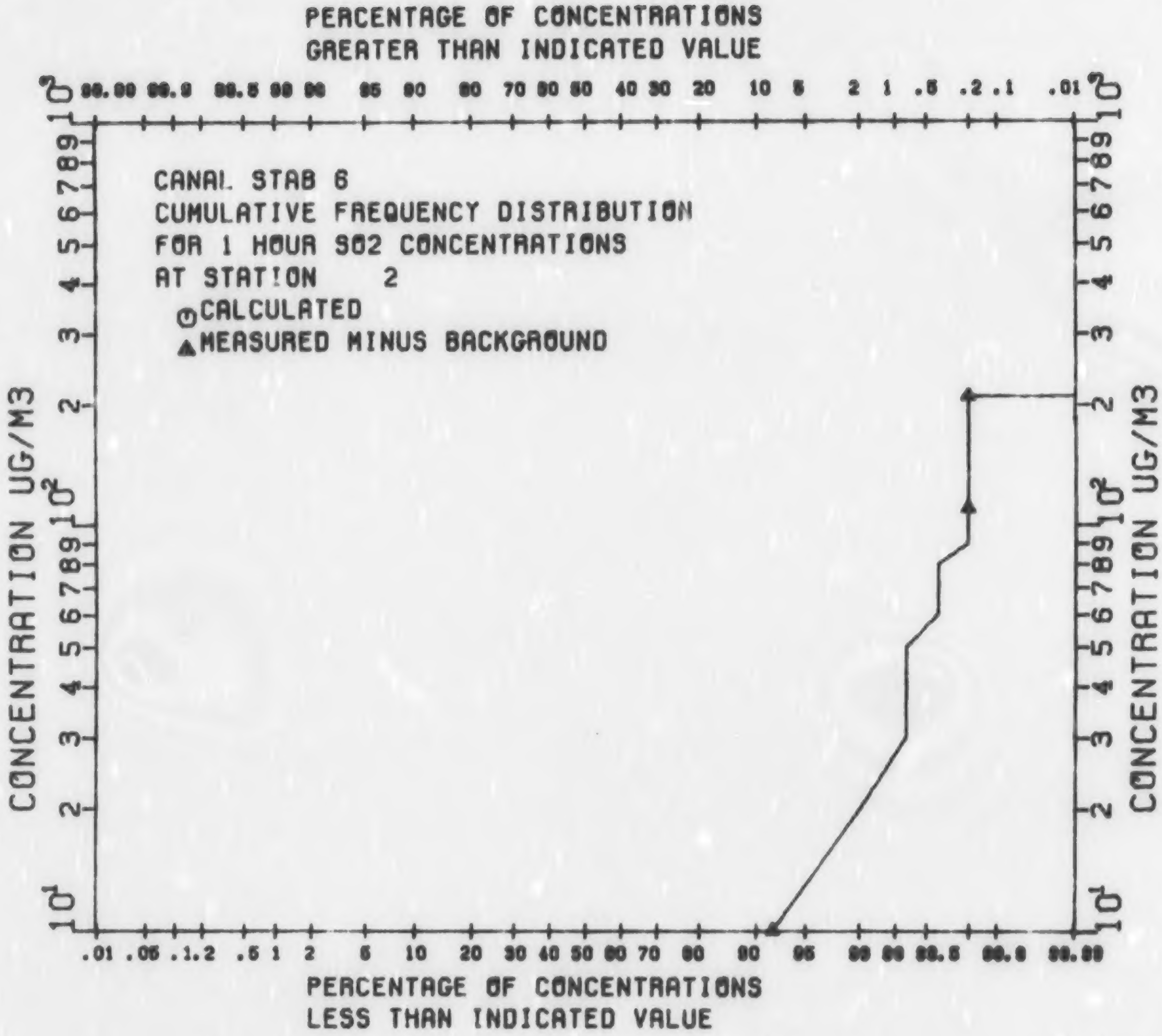

Figure A-12b. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 2 for stability F

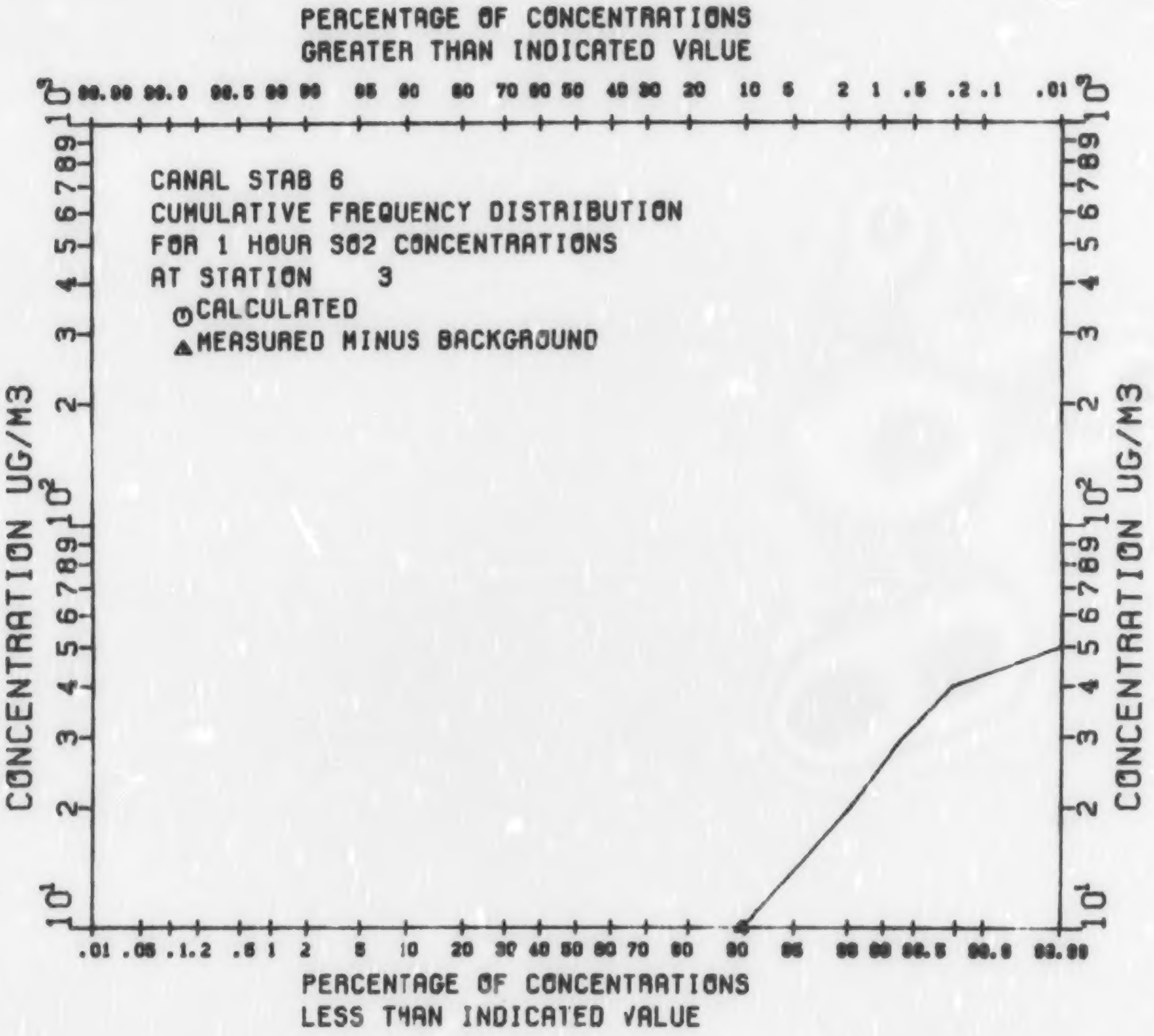

Figure A-12c. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 3 for stability F

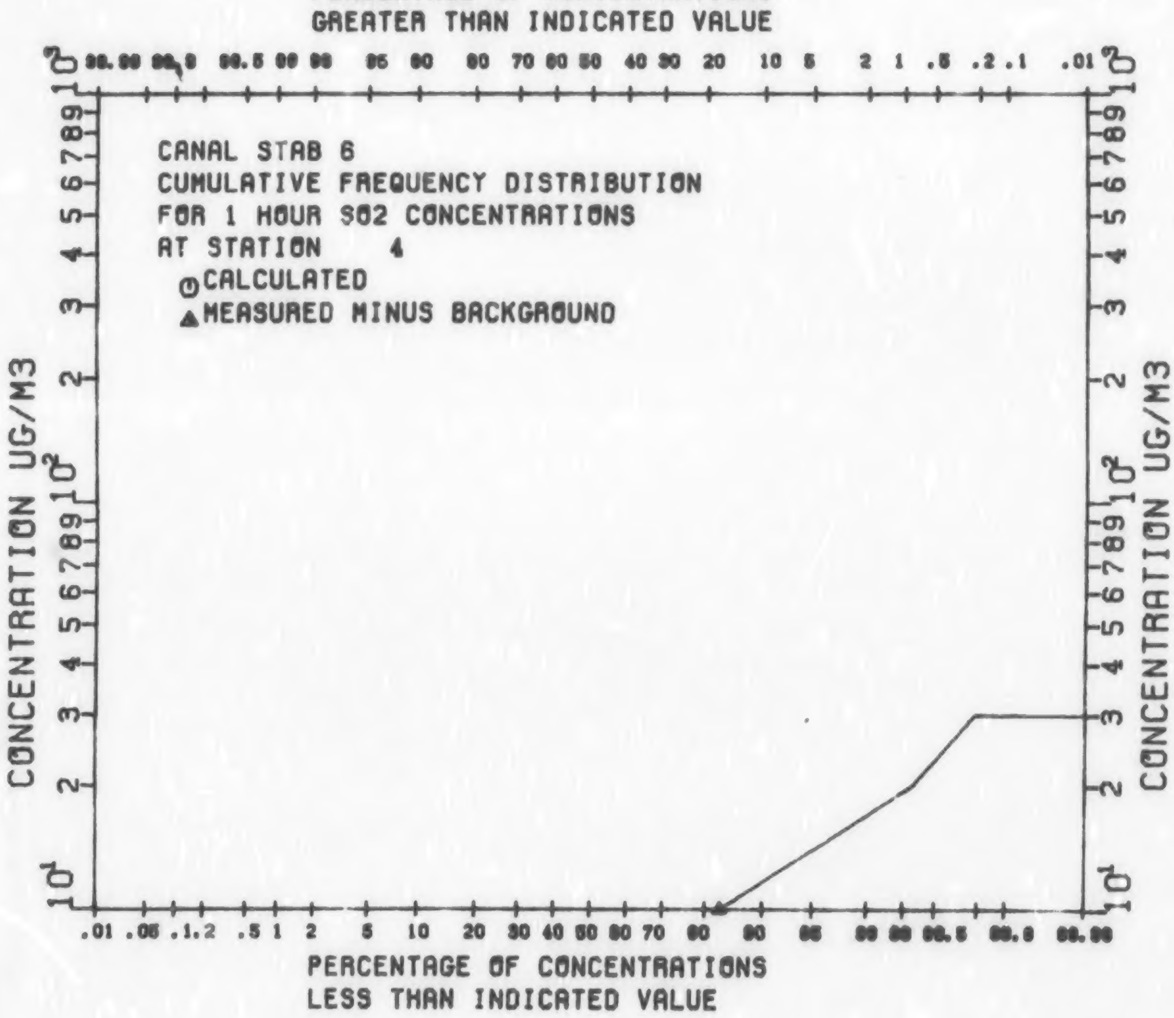

Figure A-12d. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 4 for stability F

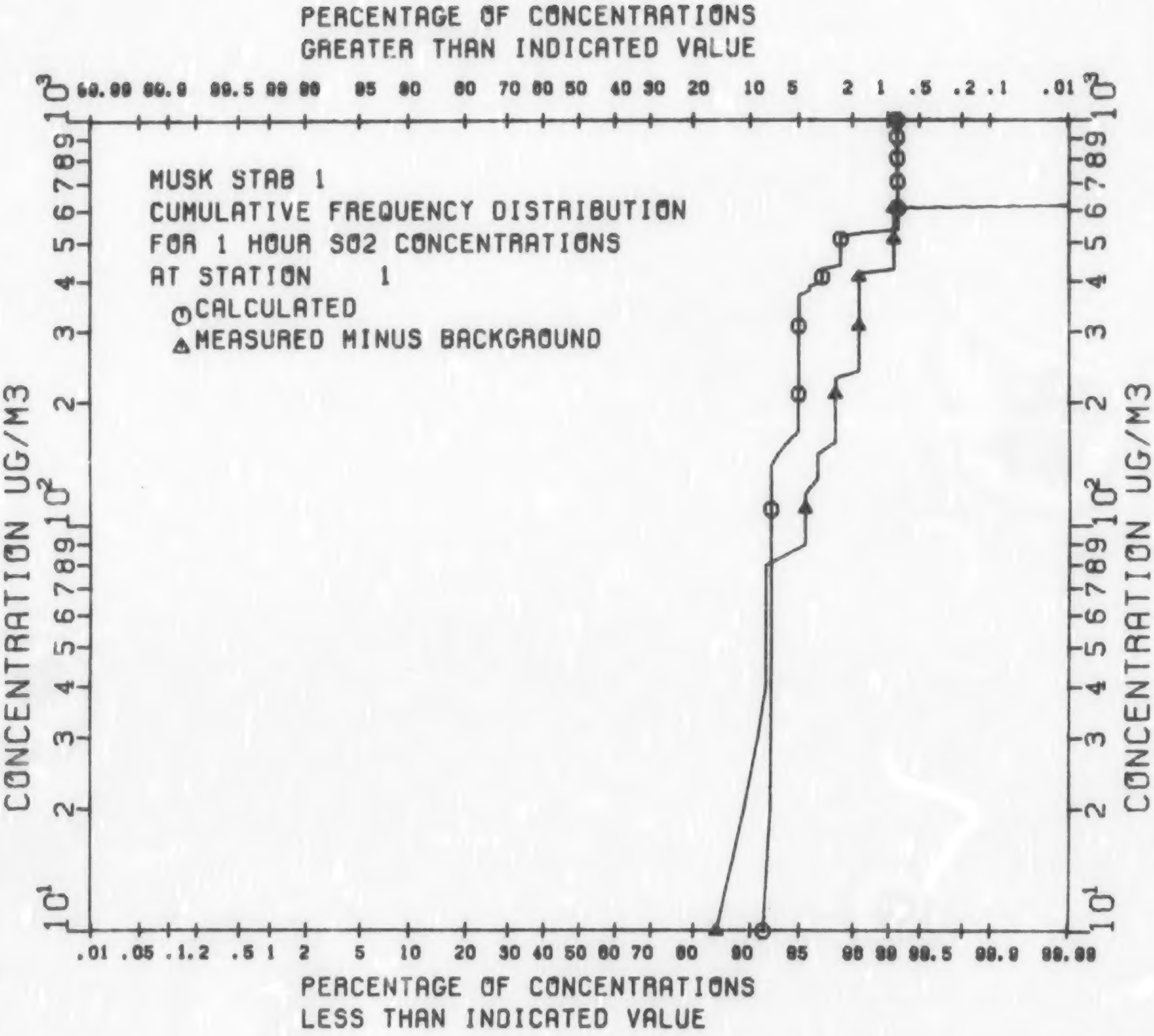

Figure A-13a. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 1 for stability A

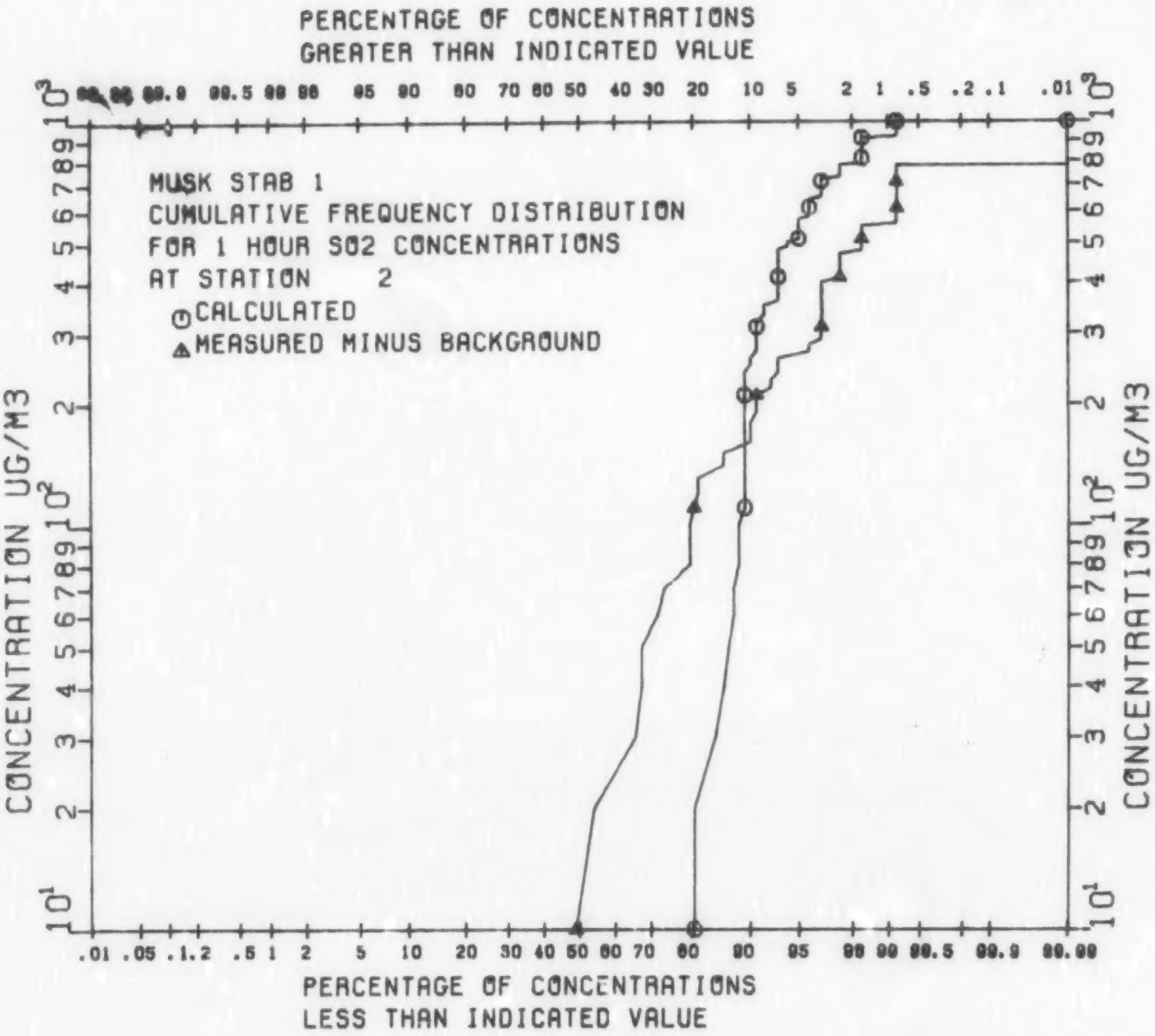

Figure A-13b. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 2 for stability A

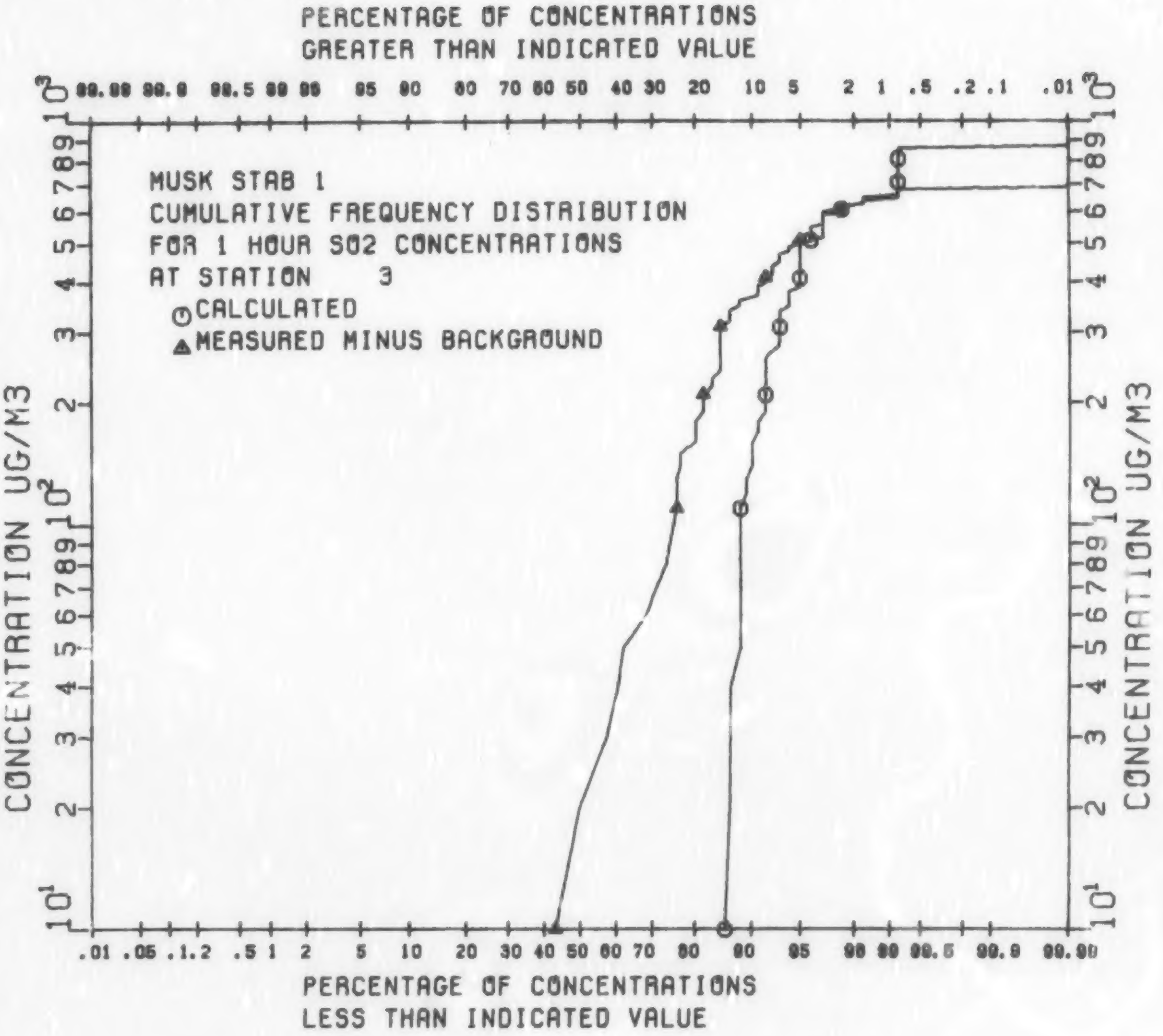

Figure A-13c. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 3 for stability A

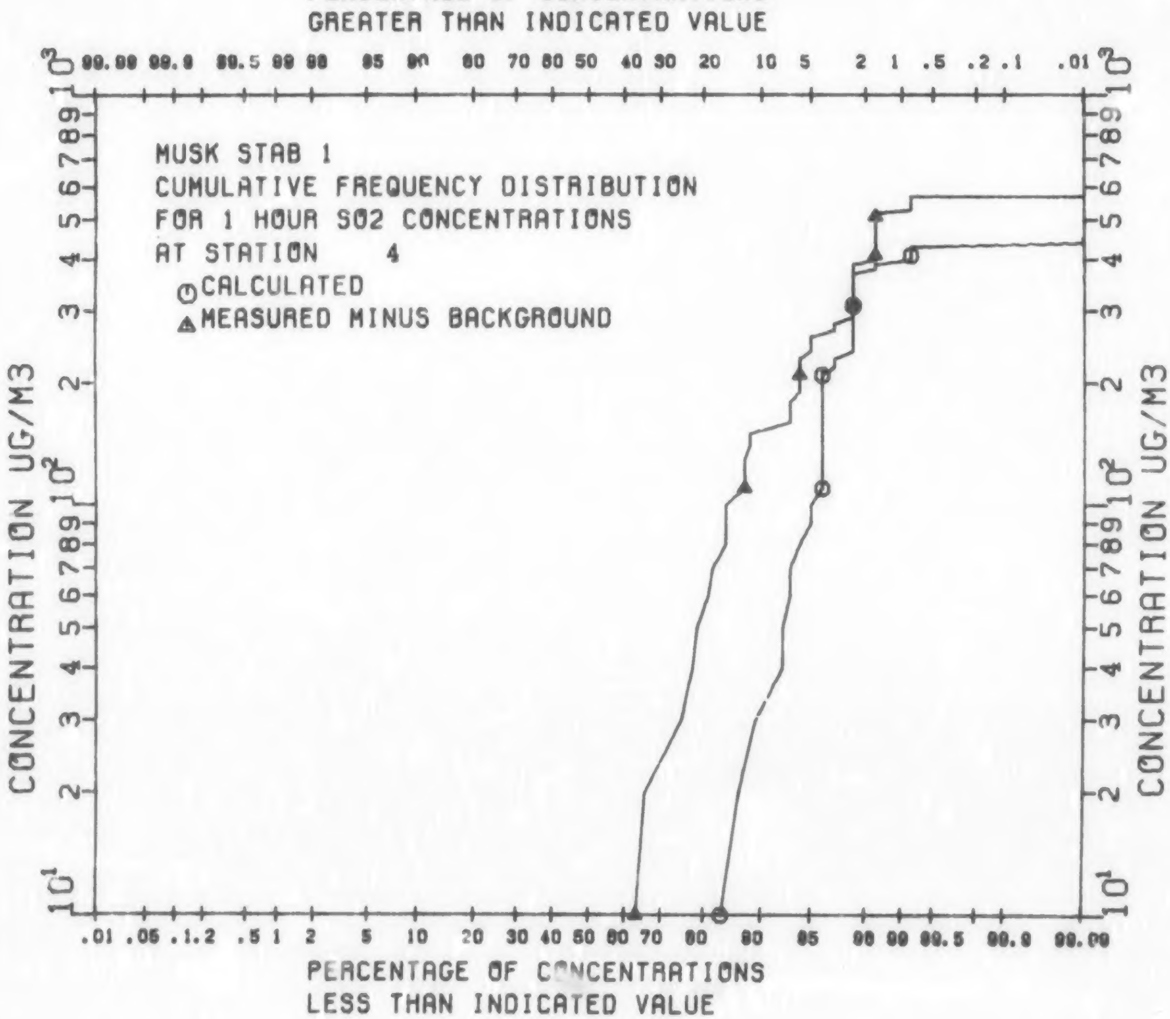

Figure A-13d. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 4 for stability A

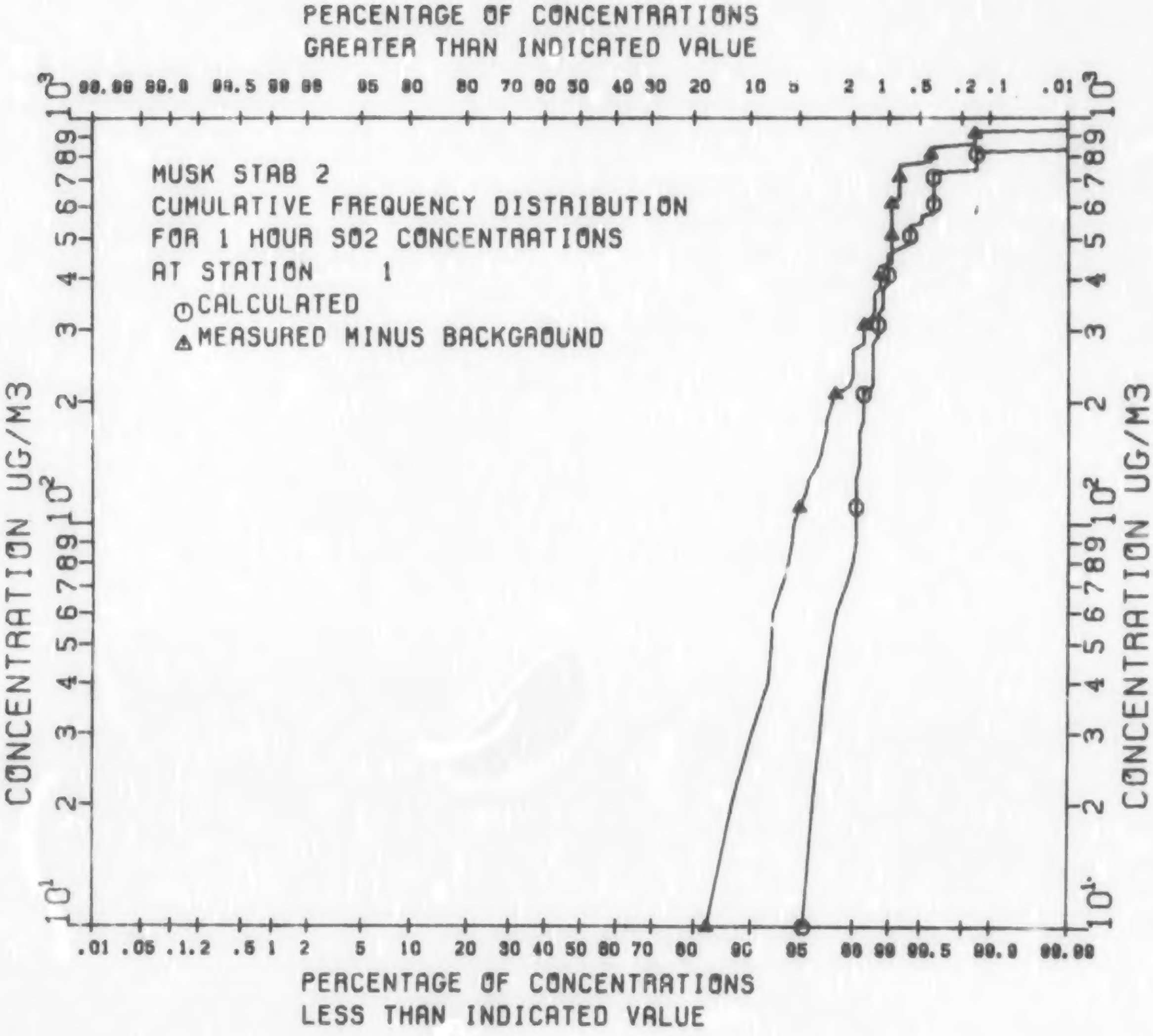

Figure A-14a. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 1 for stability B

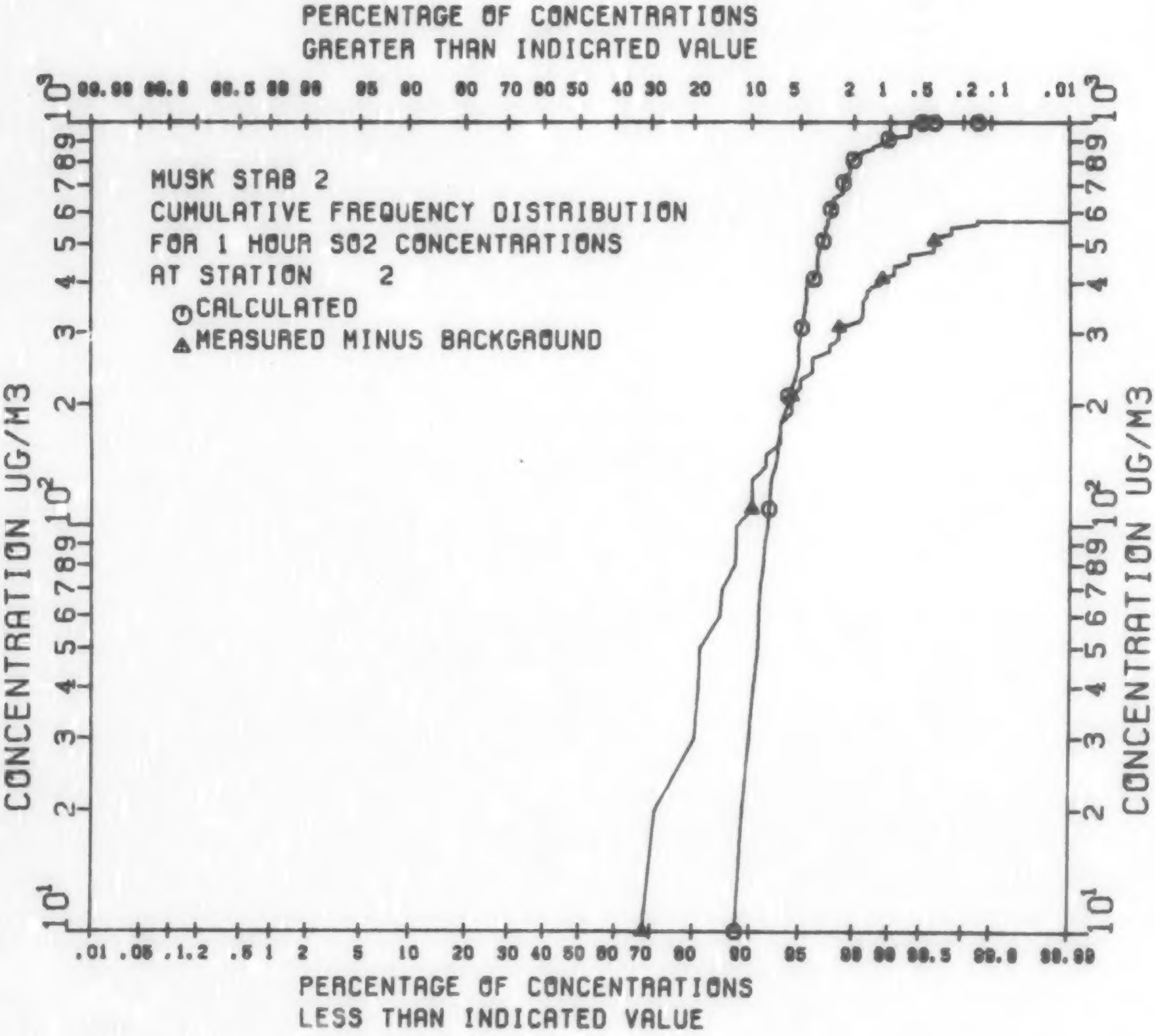

Figure A-14b. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 2 for stability B

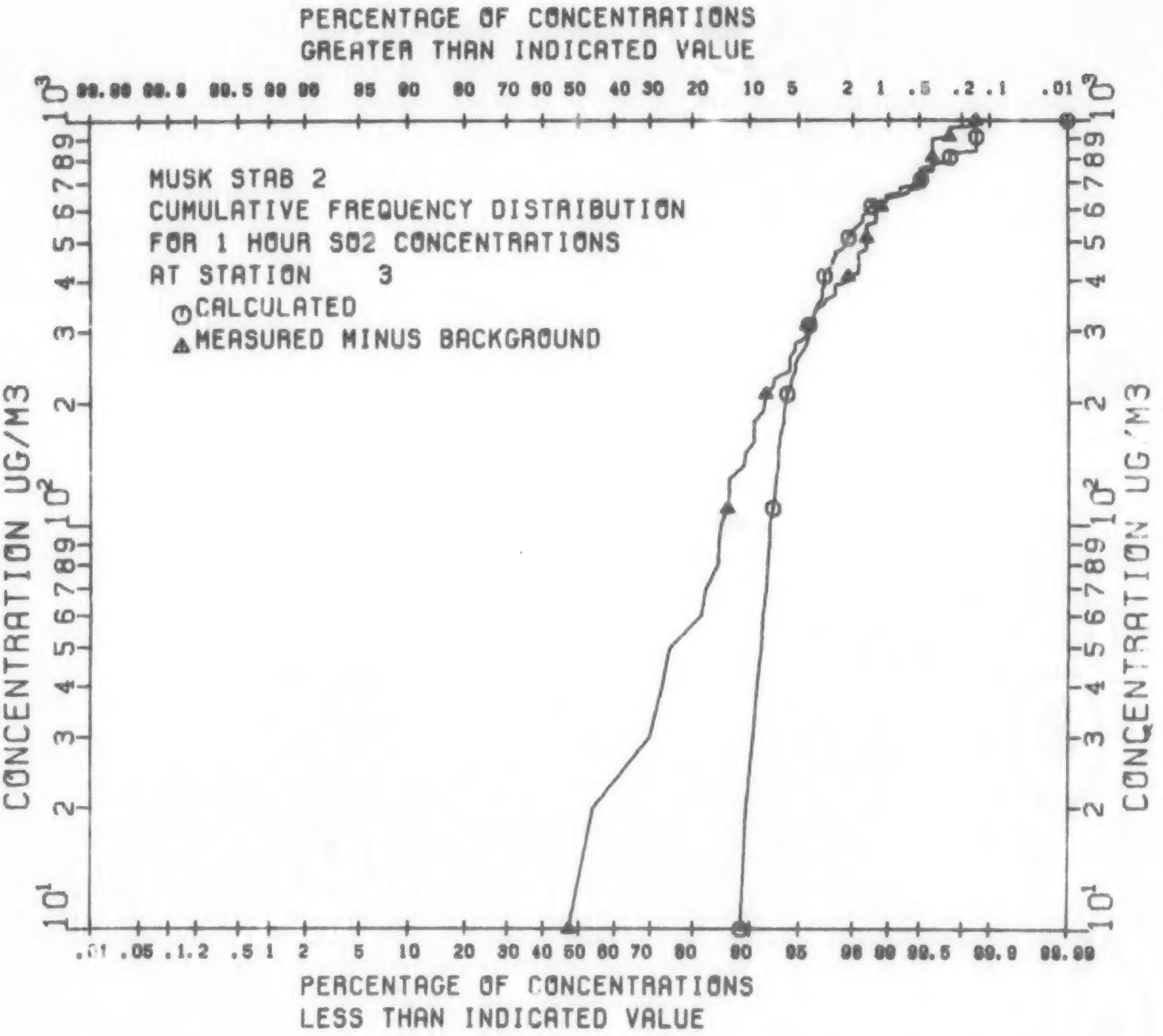

Figure A-14c. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 3 for stability B

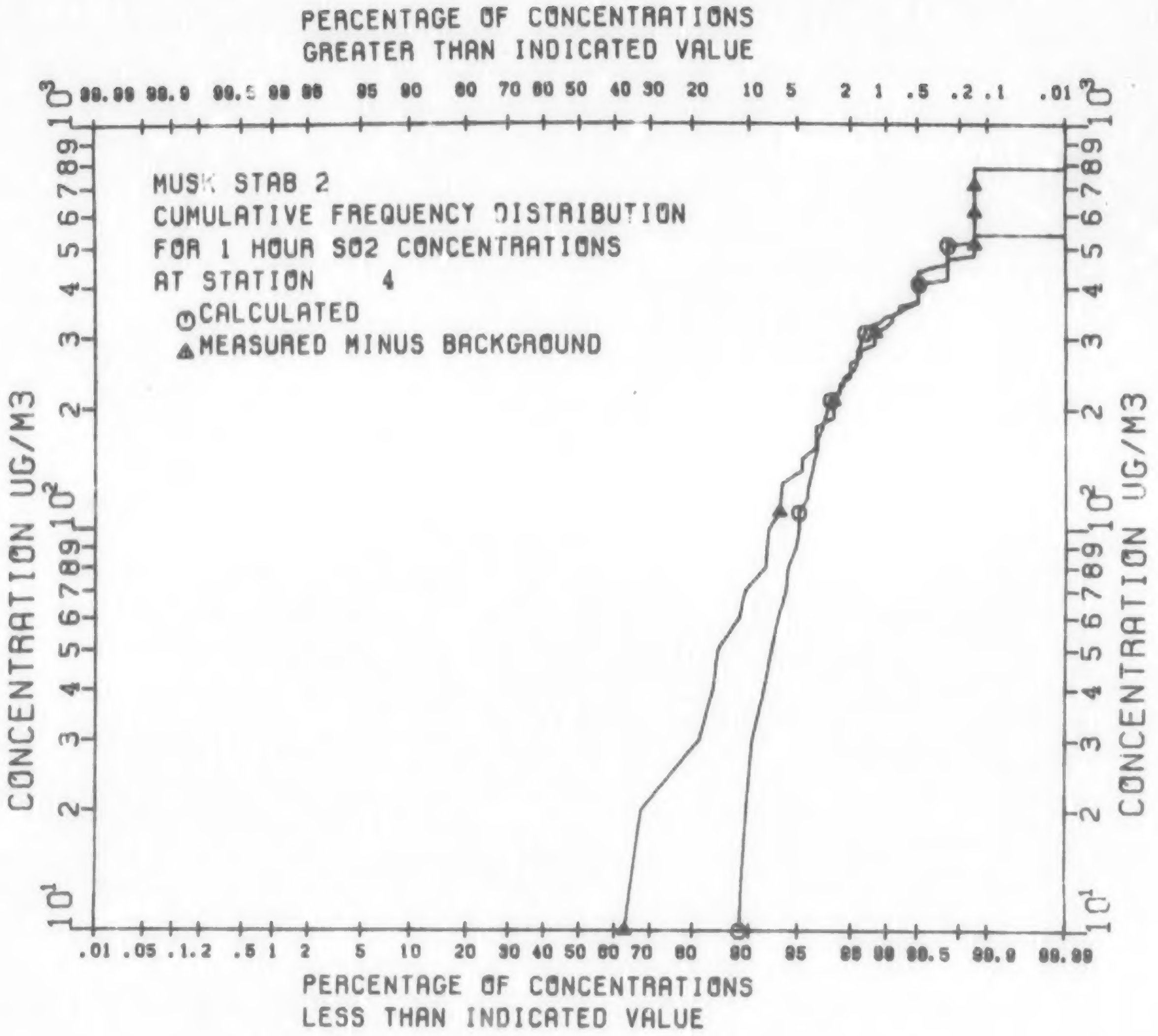

Figure A-14d. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 4 for stability B

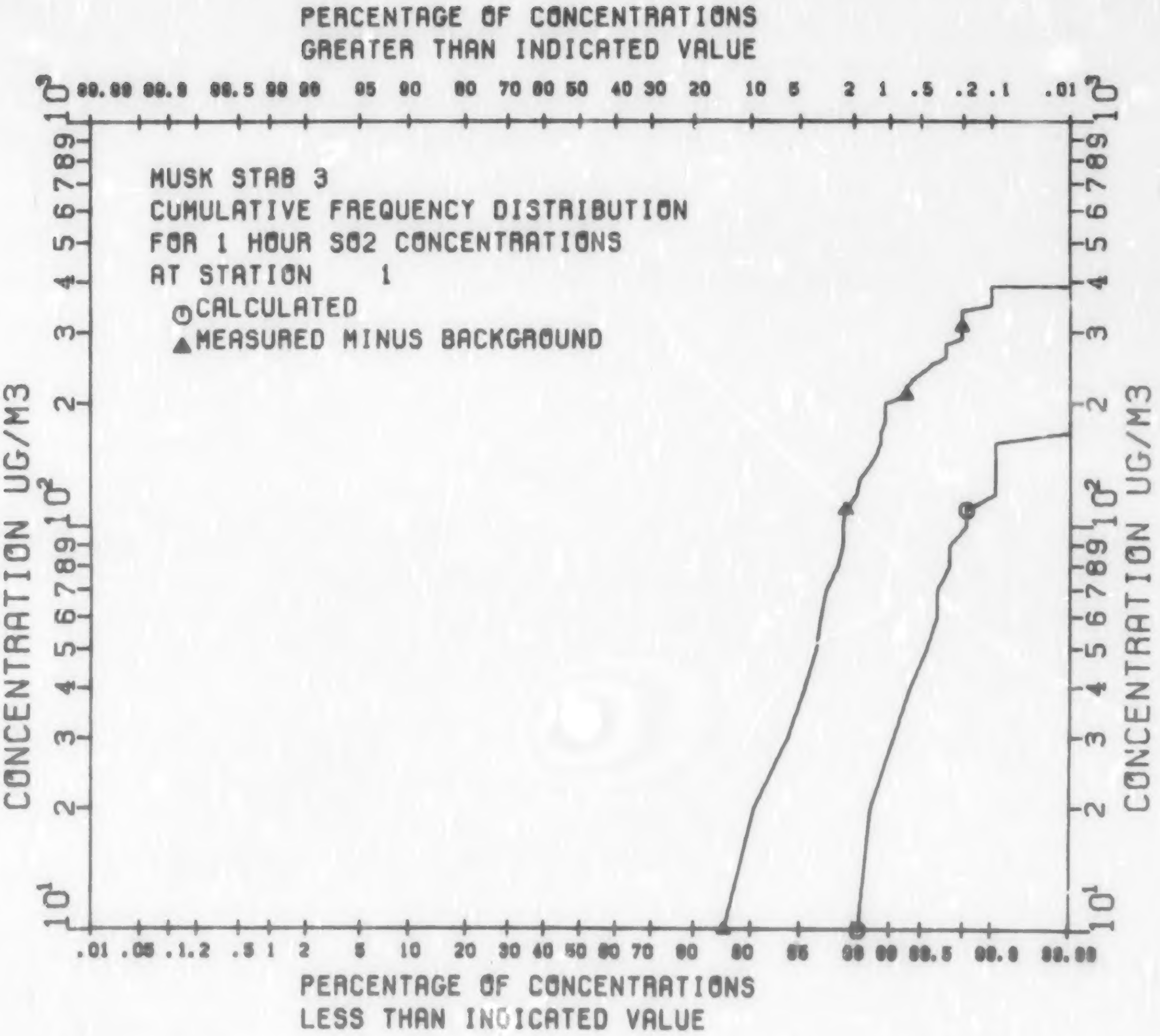

Figure A-15a. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 1 for stability C

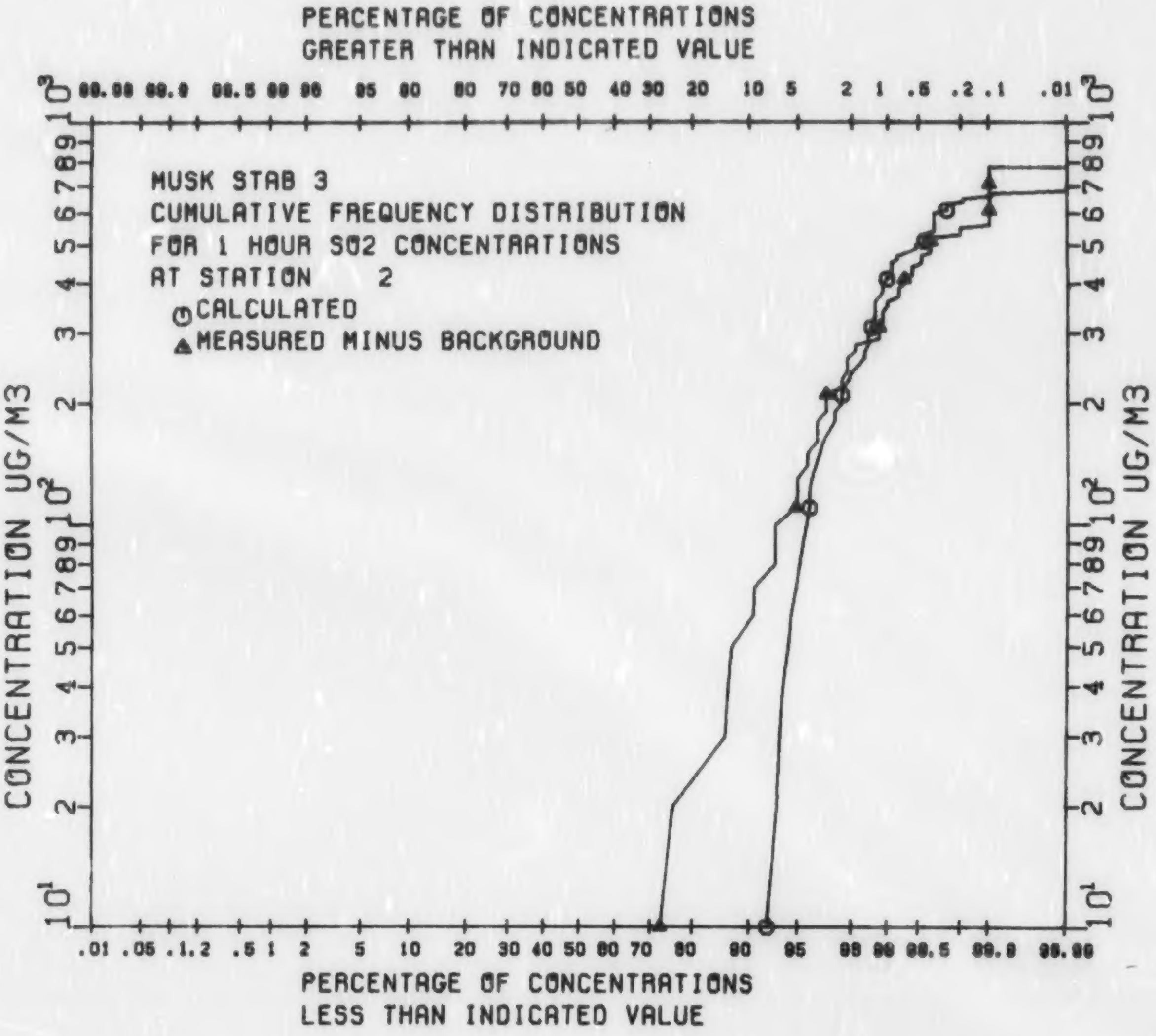

Figure A-15b. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 2 for stability C

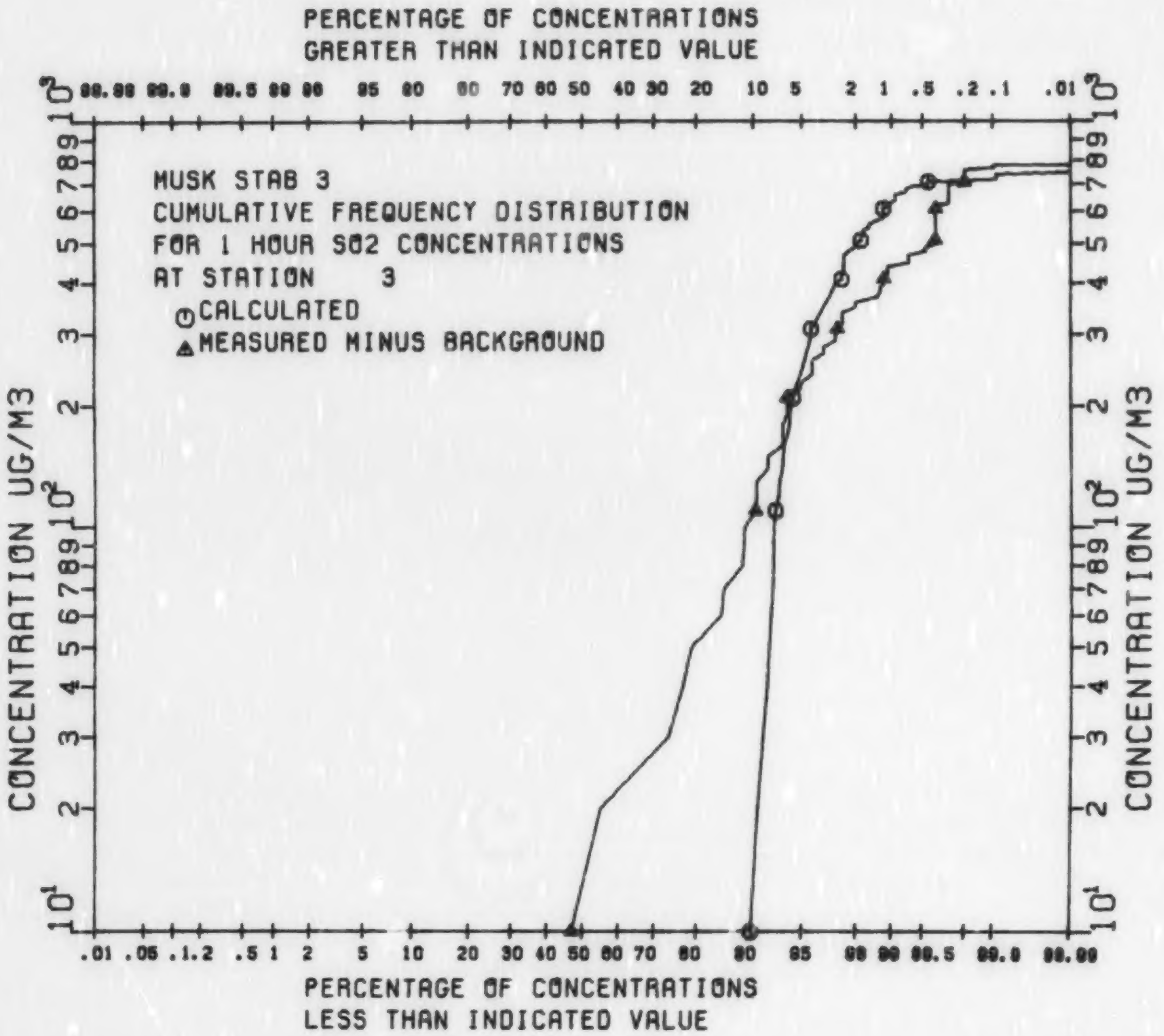

Figure A-15c. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 3 for stability C

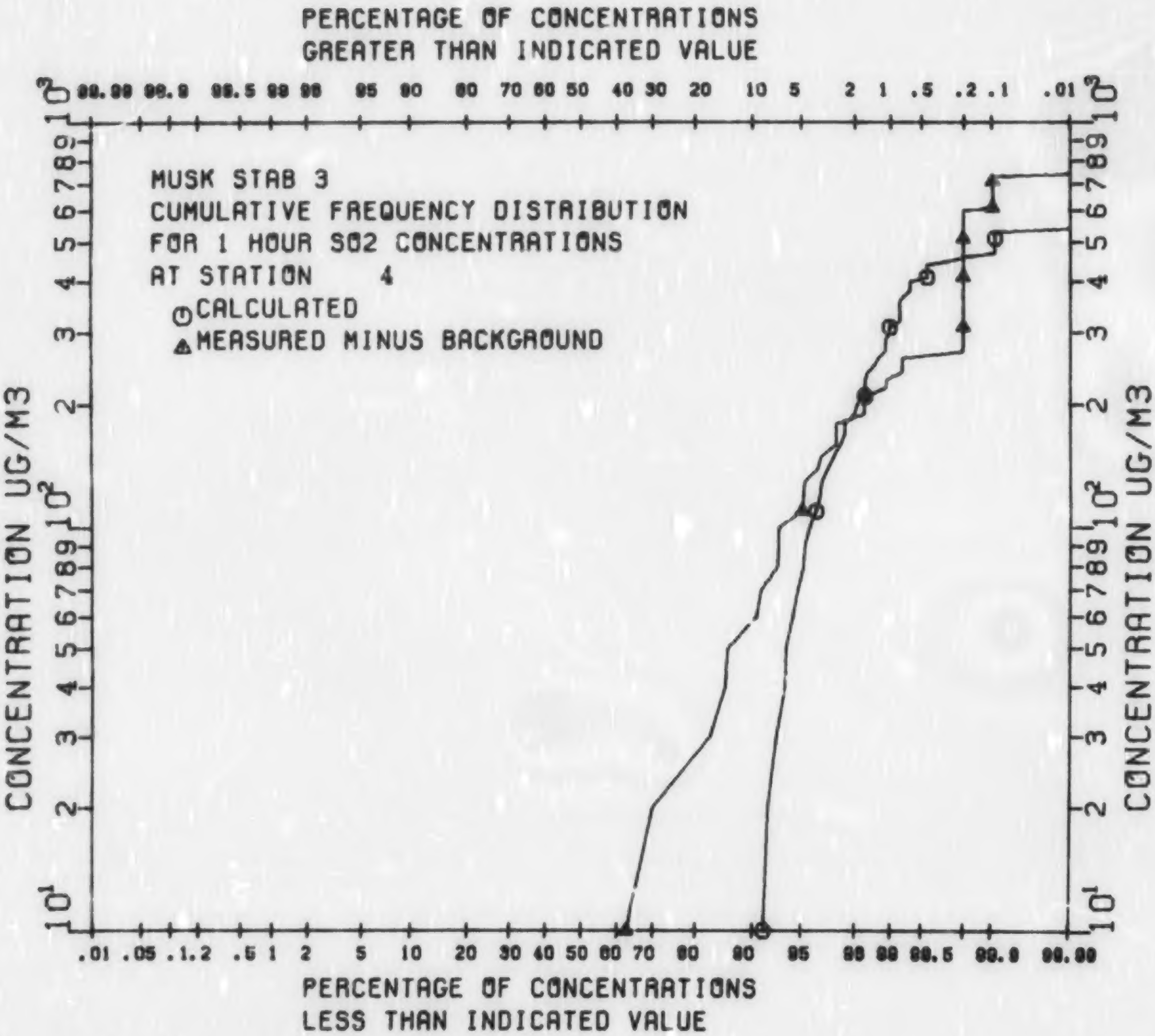

Figure A-15d. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 4 for stability C

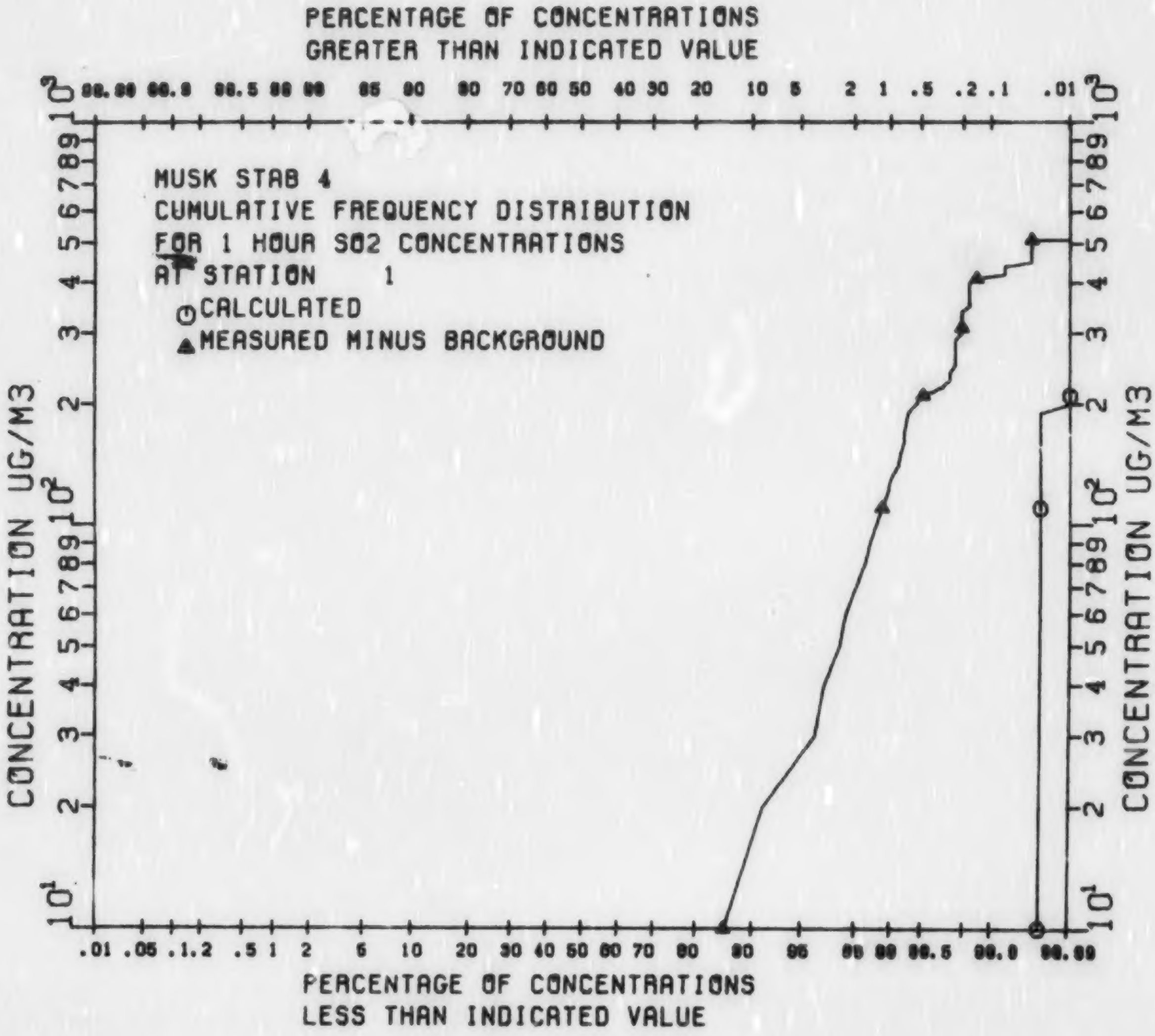

Figure A-16a. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 1 for stability D

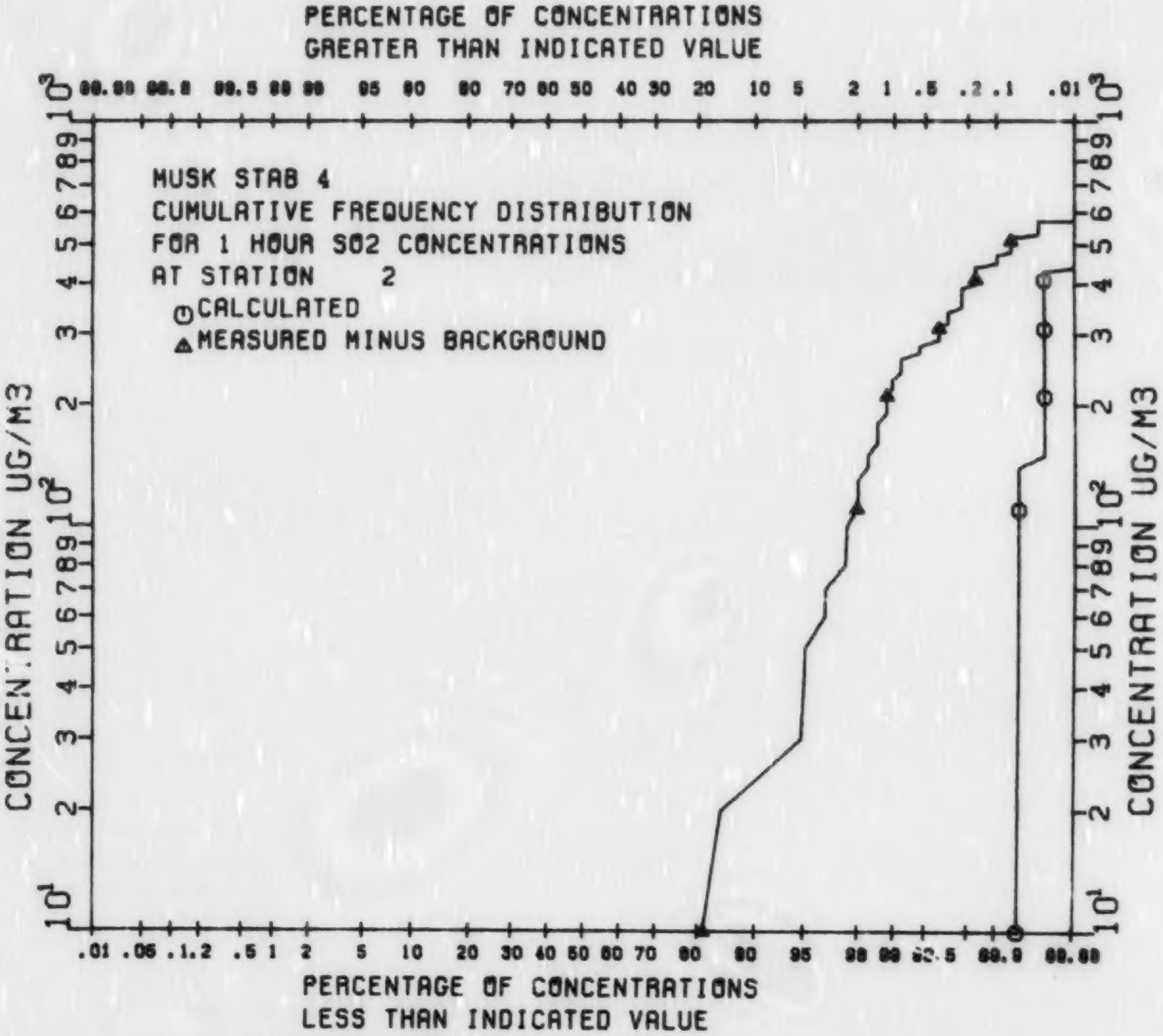

Figure A-16b. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 2 for stability D

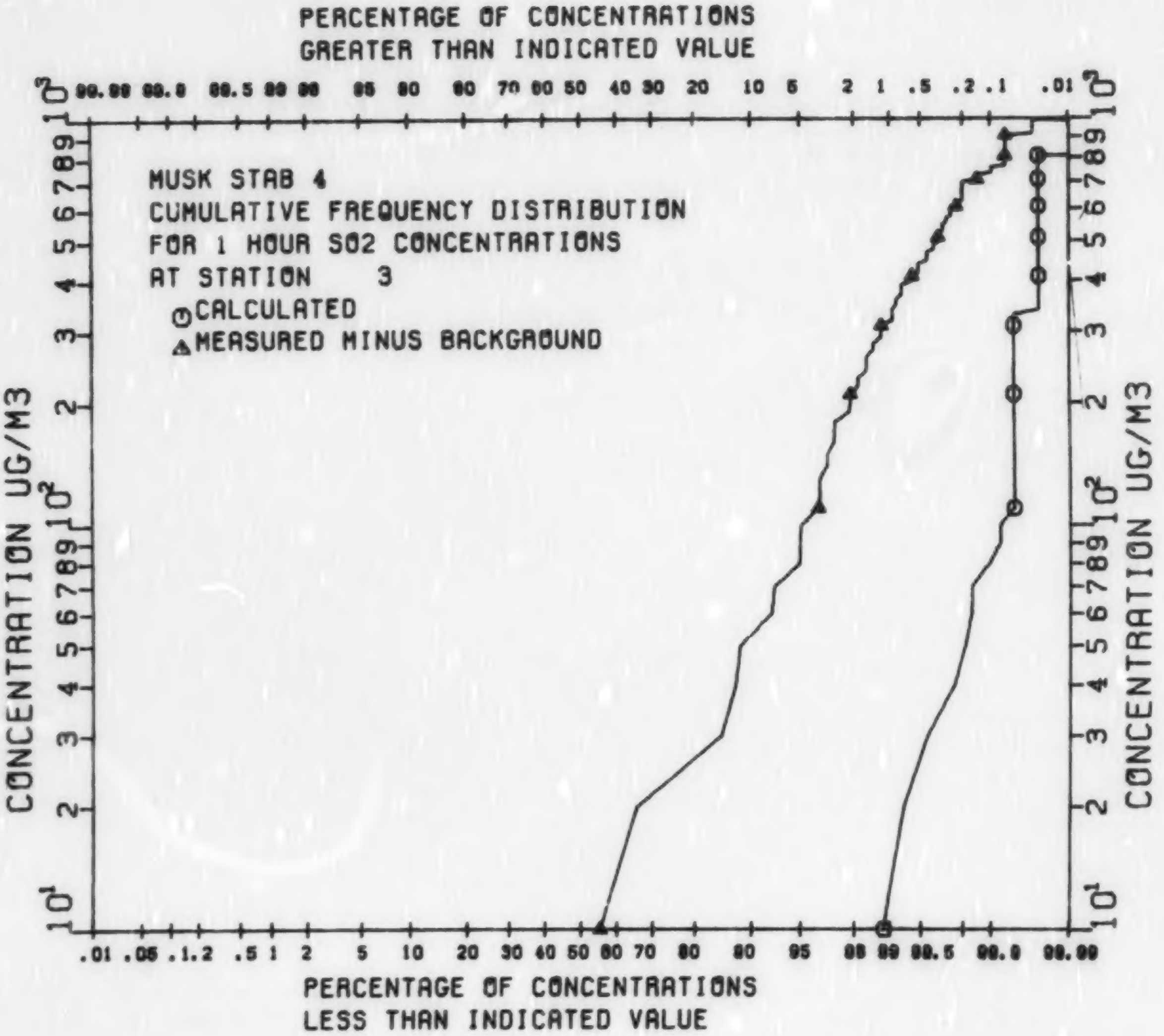

Figure A-16c. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 3 for stability D

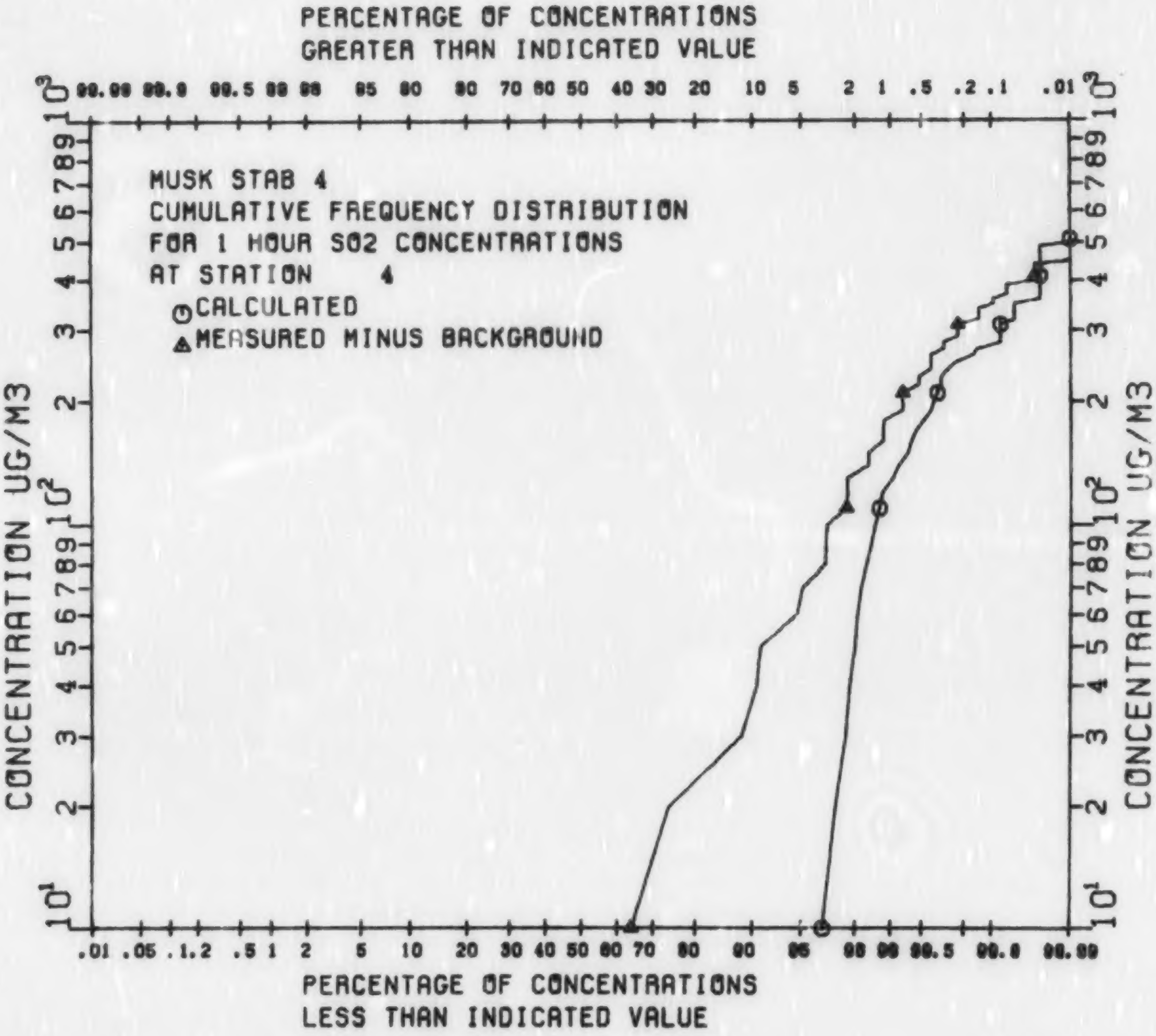

Figure A-16d. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 4 for stability D

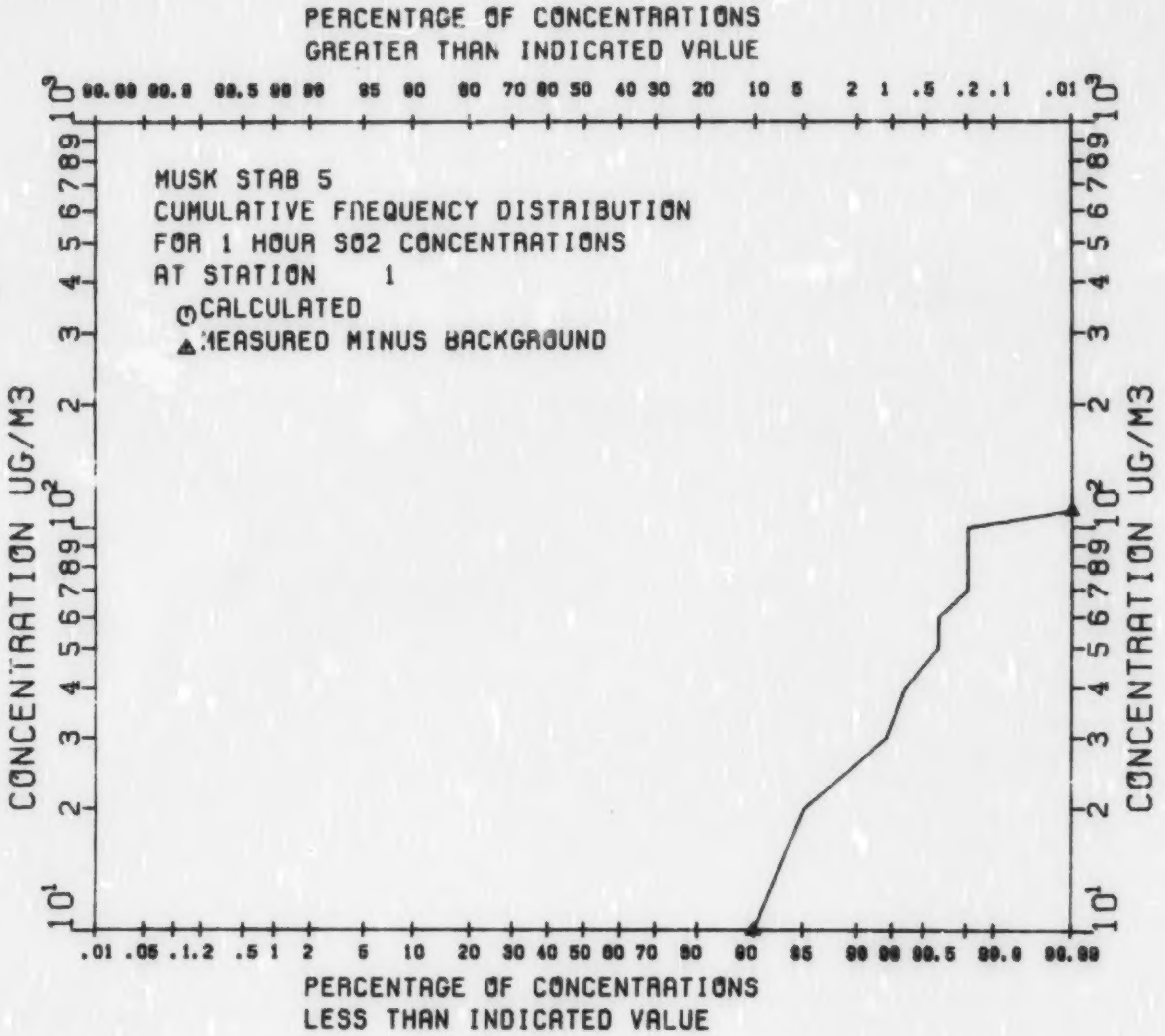

Figure A-17a. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 1 for stability E

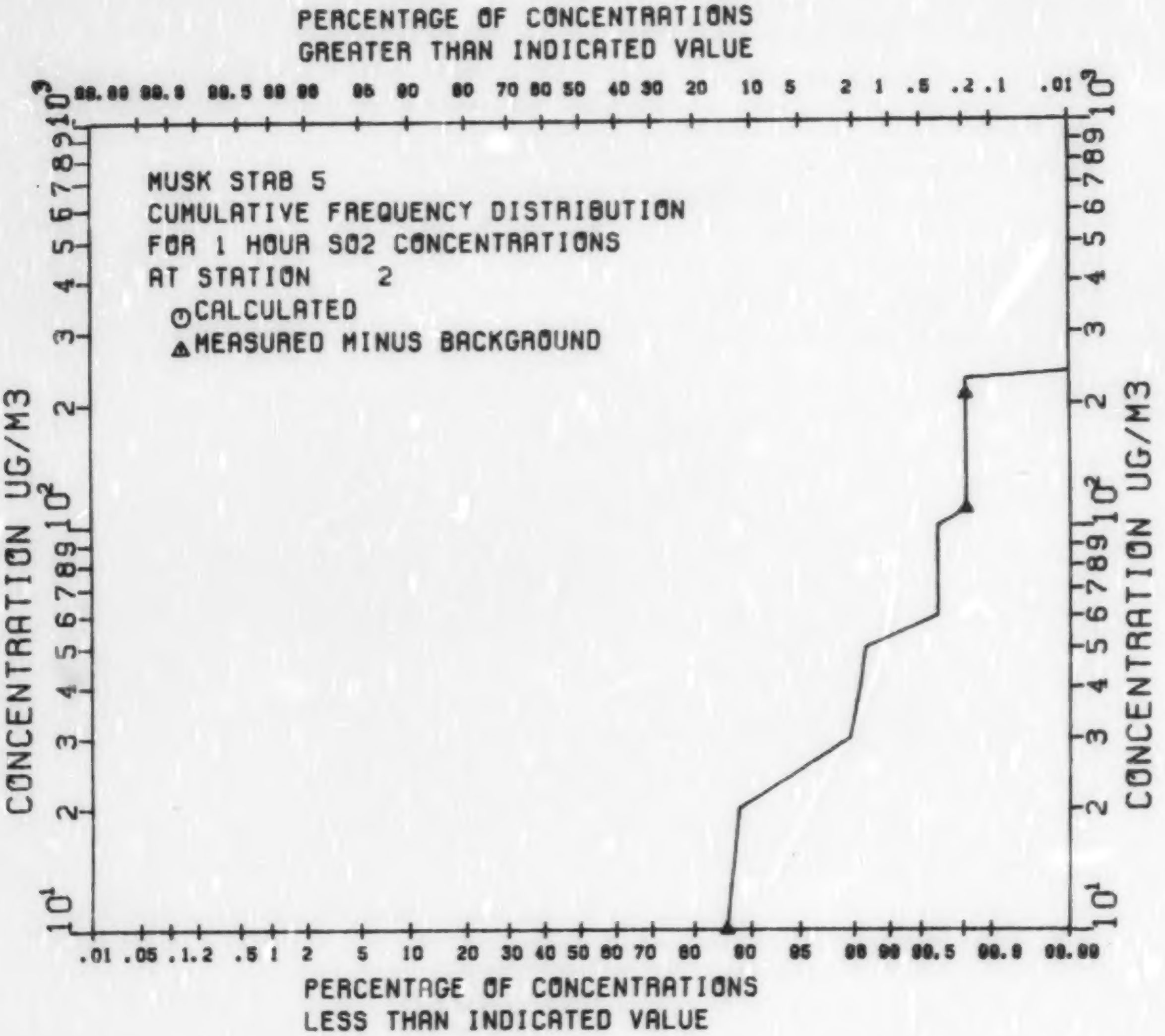

Figure A-17b. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 2 for stability E

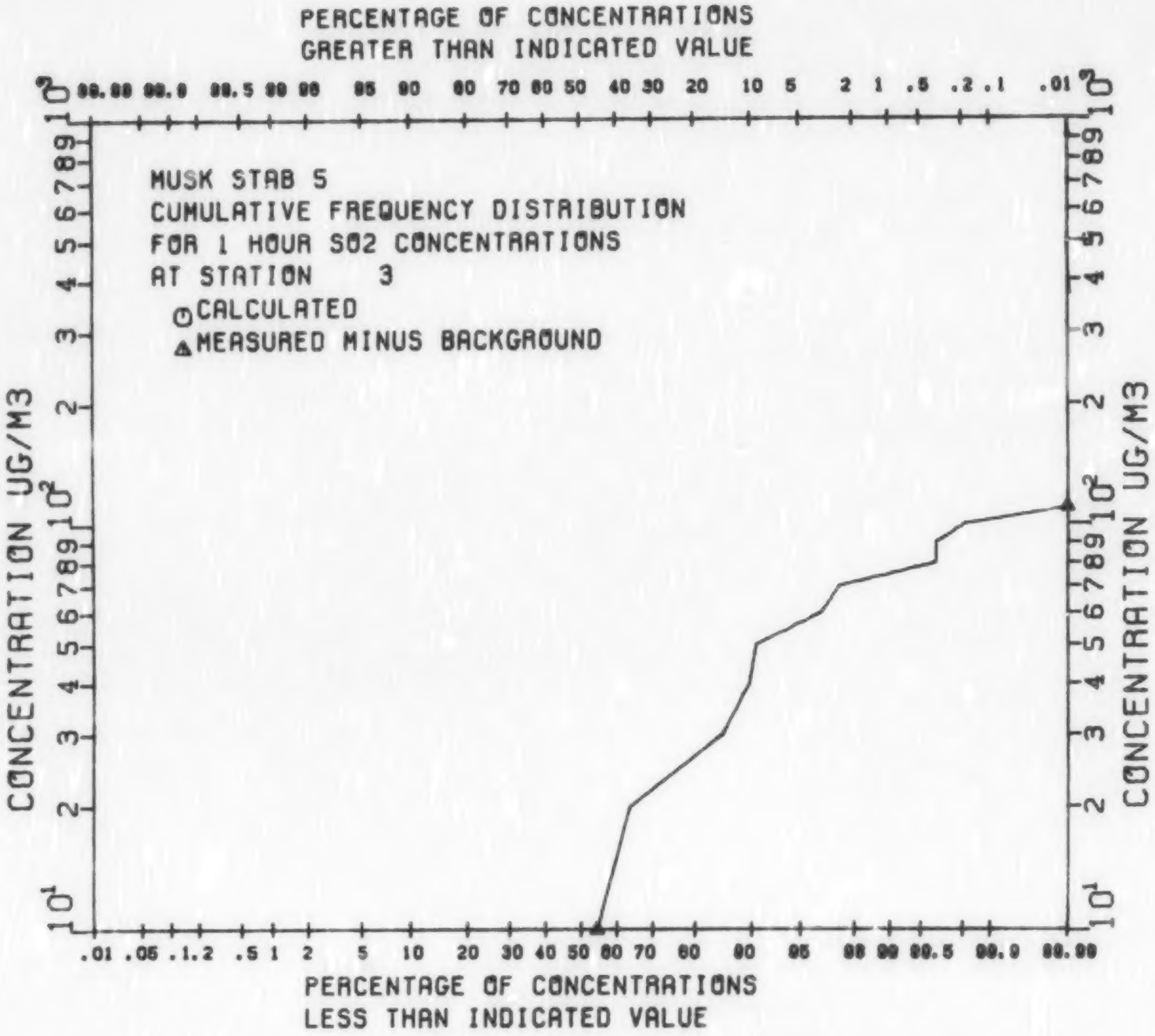

Figure A-17c. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 3 for stability E

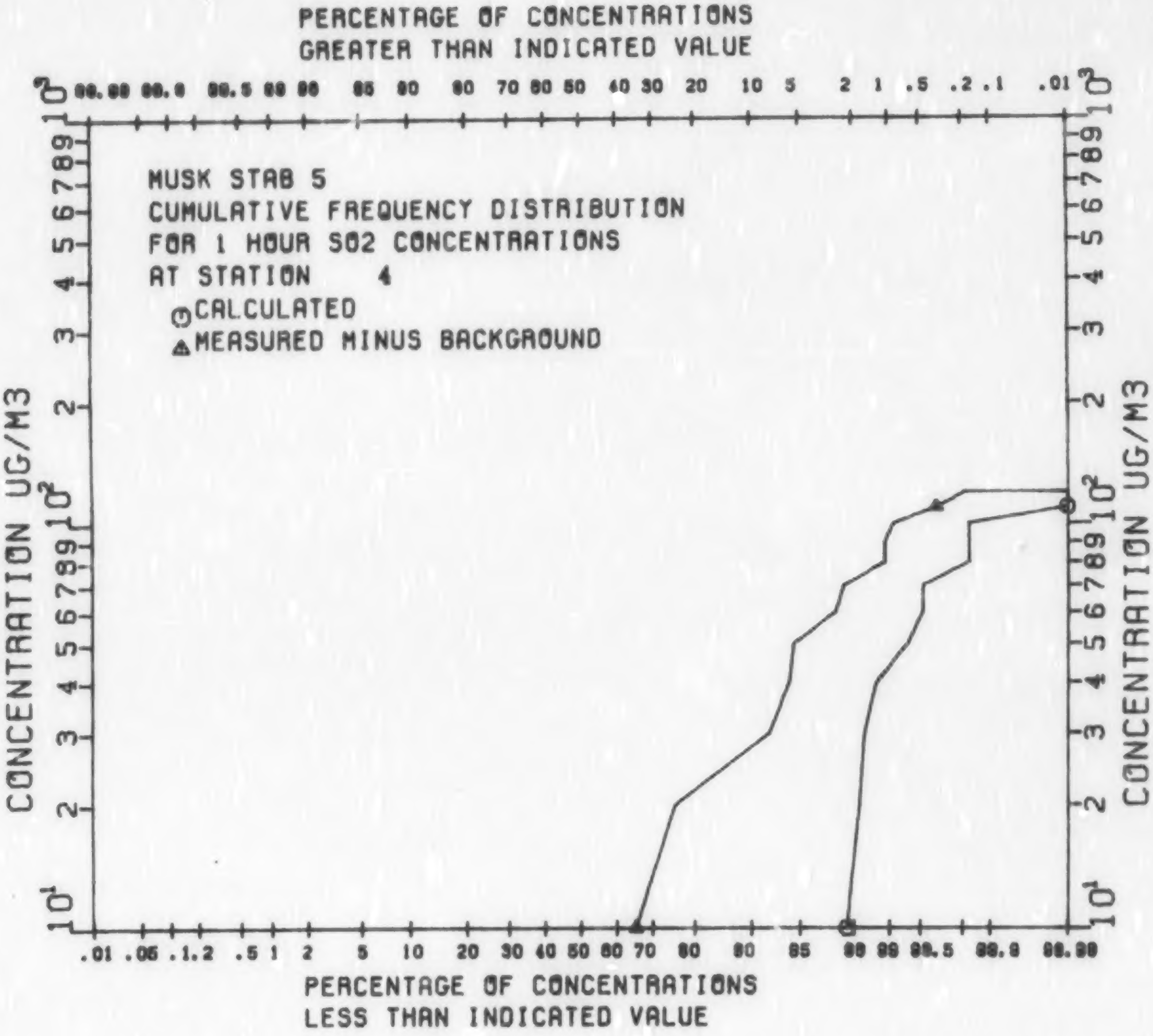

Figure A-17d. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 4 for stability E

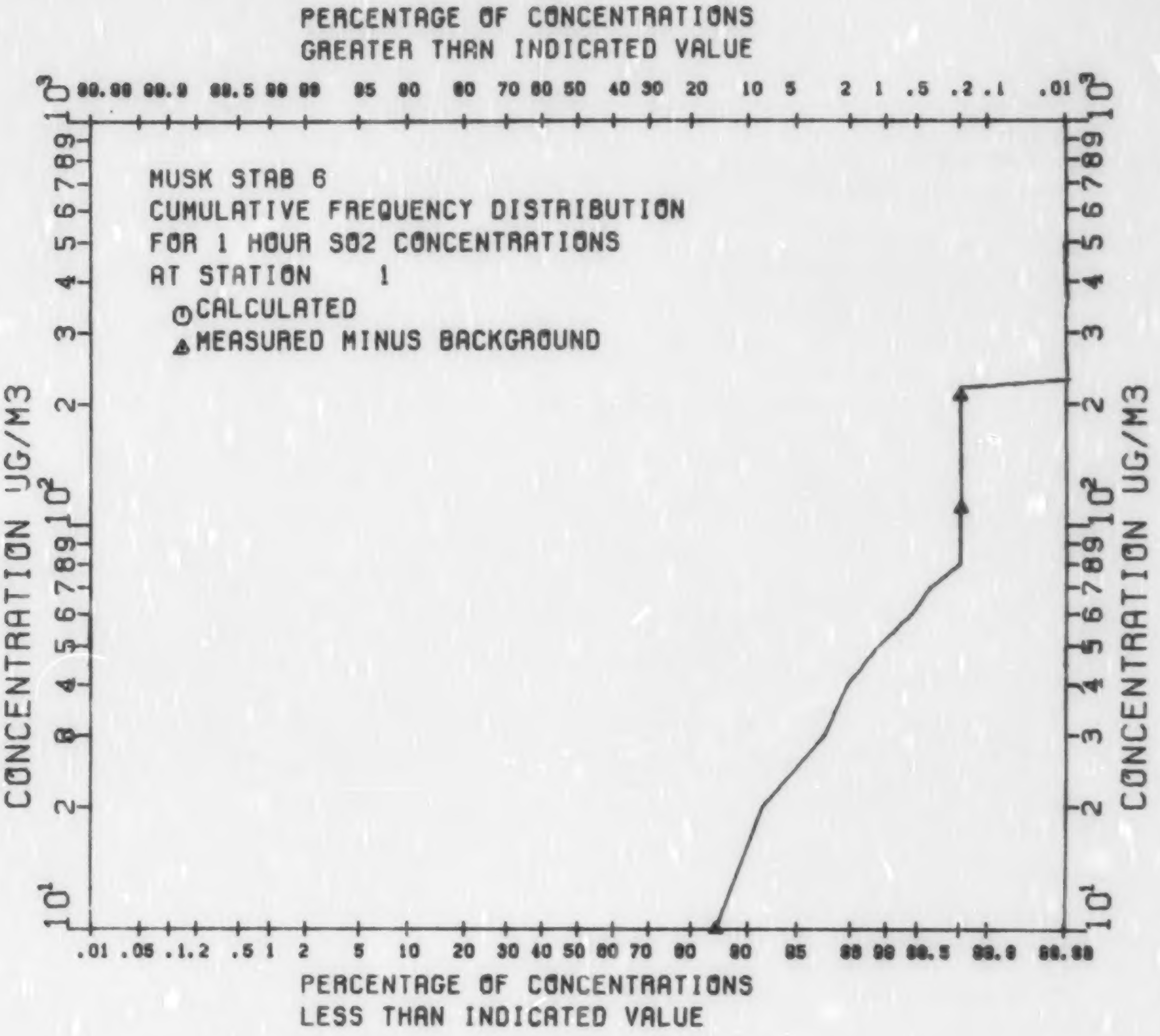

Figure A-18a. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 1 for stability F

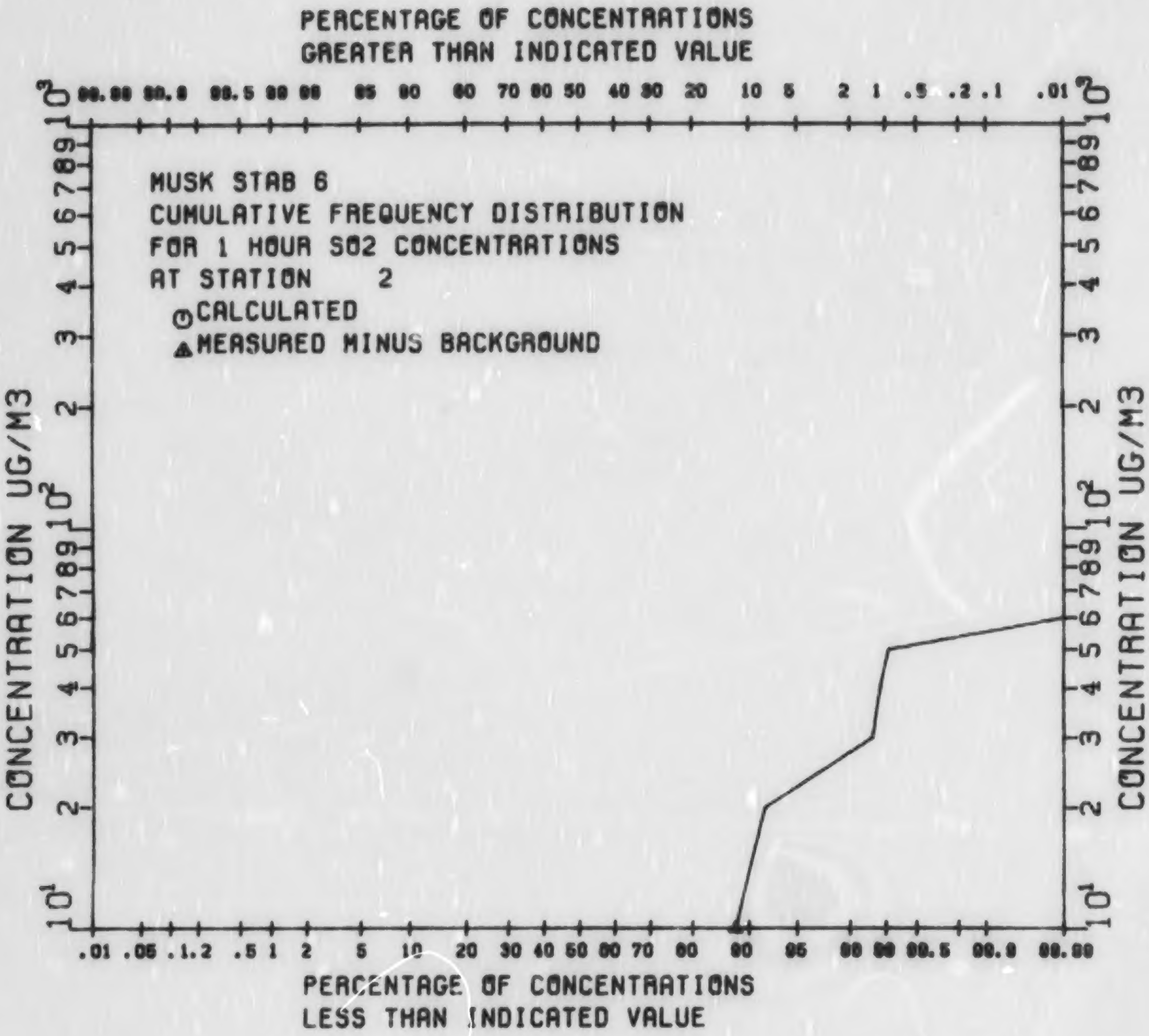

Figure A-18b. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 2 for stability F

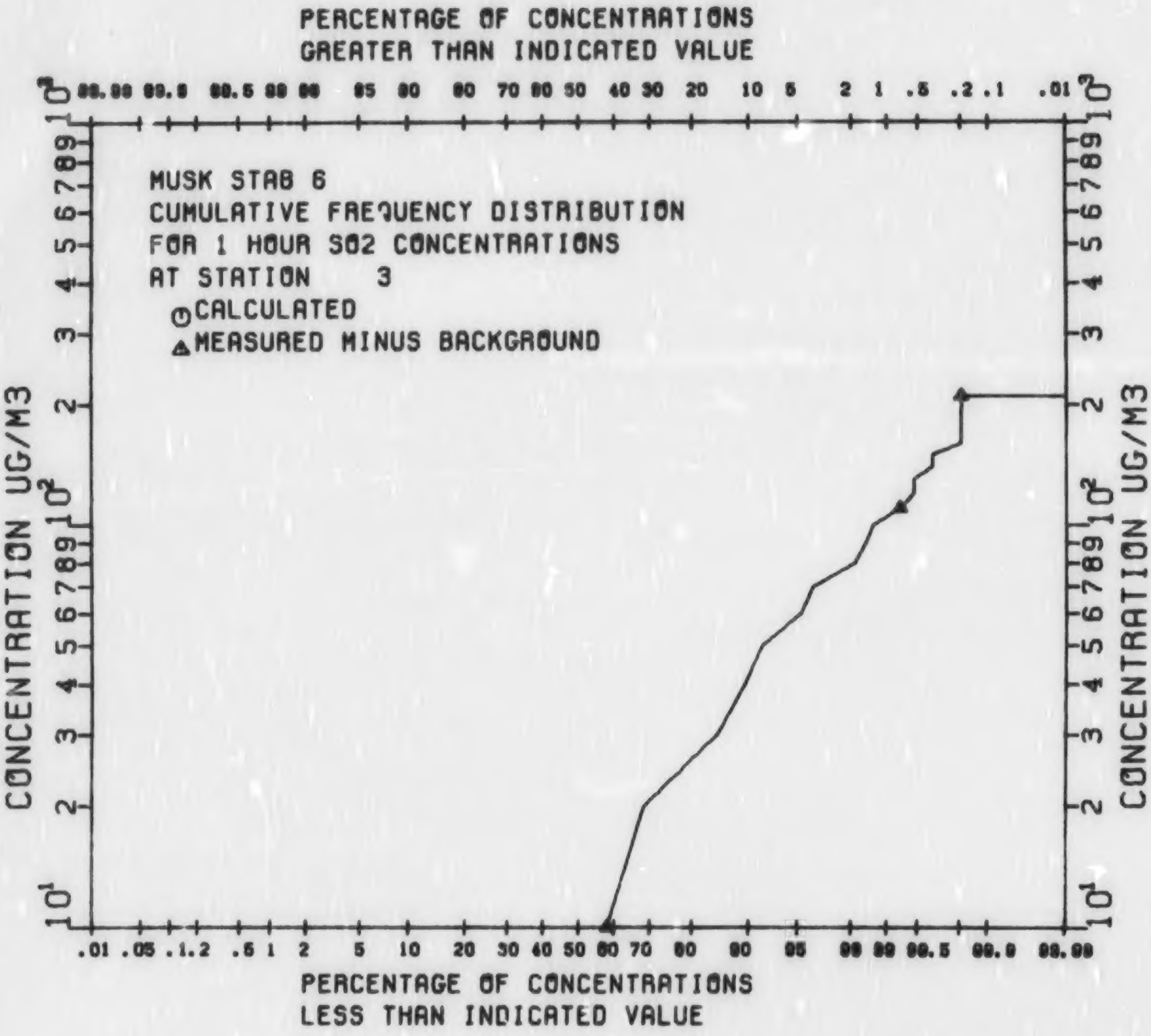

Figure A-18c. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 3 for stability F

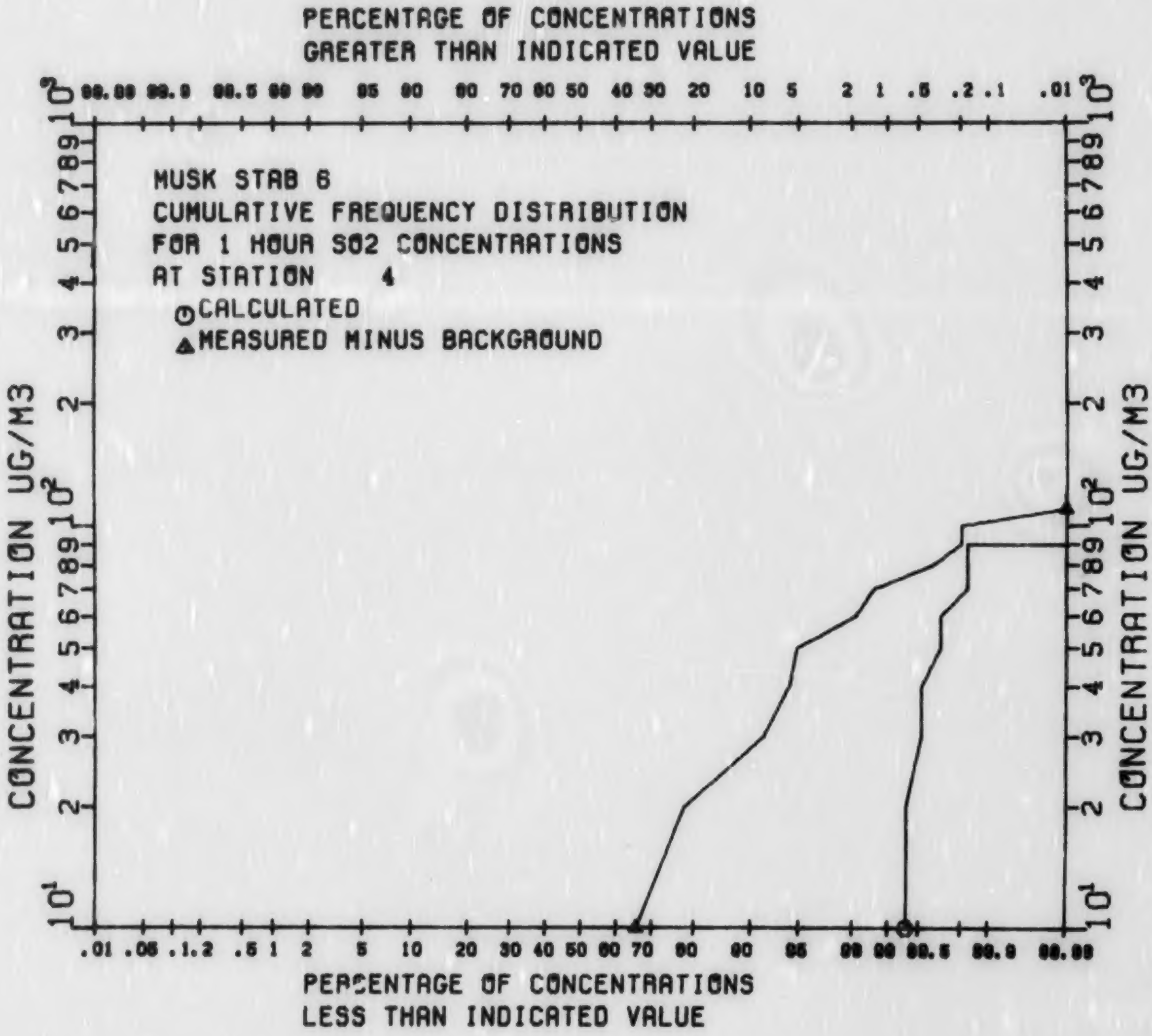

Figure A-18d. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 4 for stability F

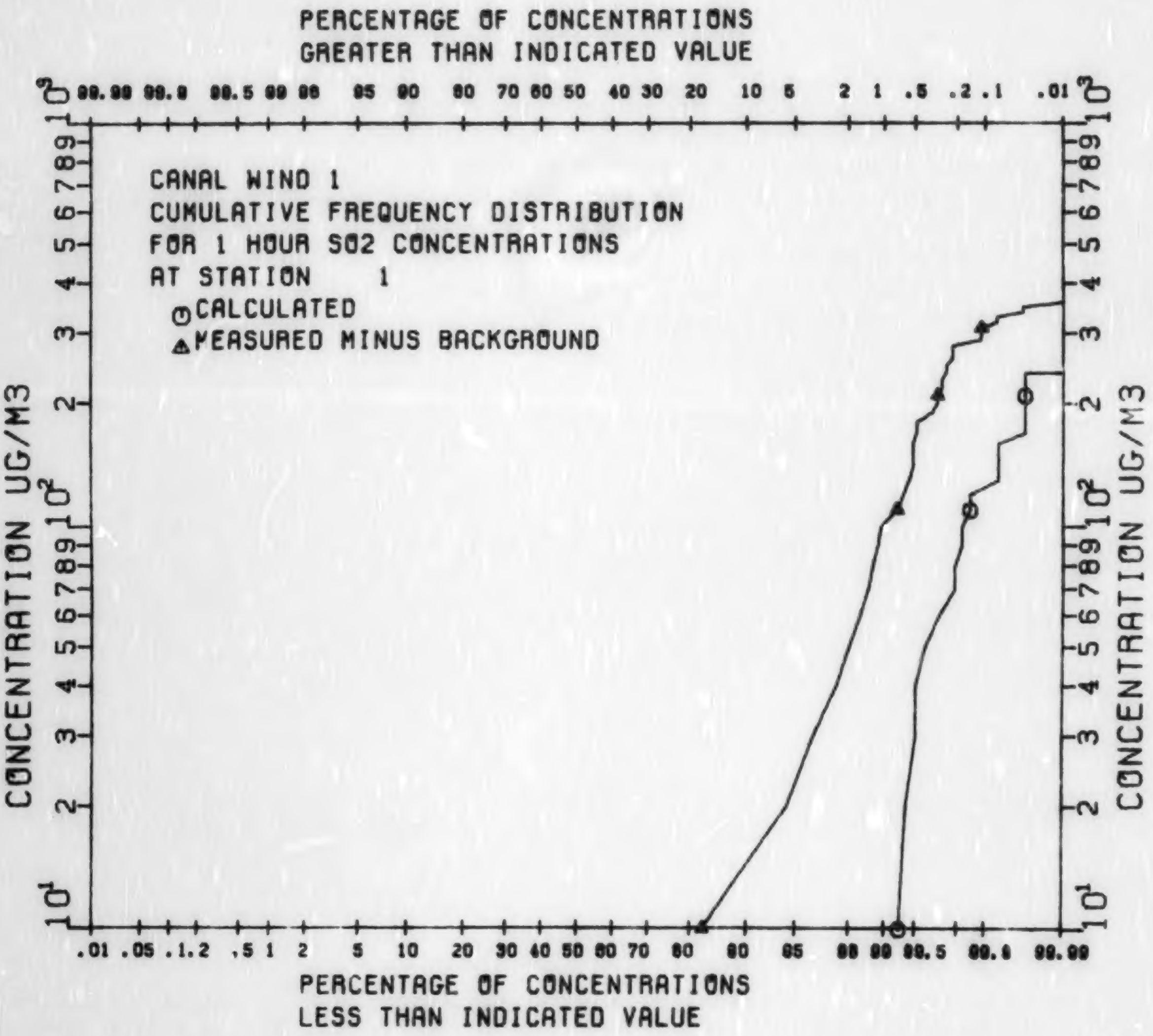

Figure A-19a. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 1 for wind speed class 1 (0 to 2.6 m/sec)

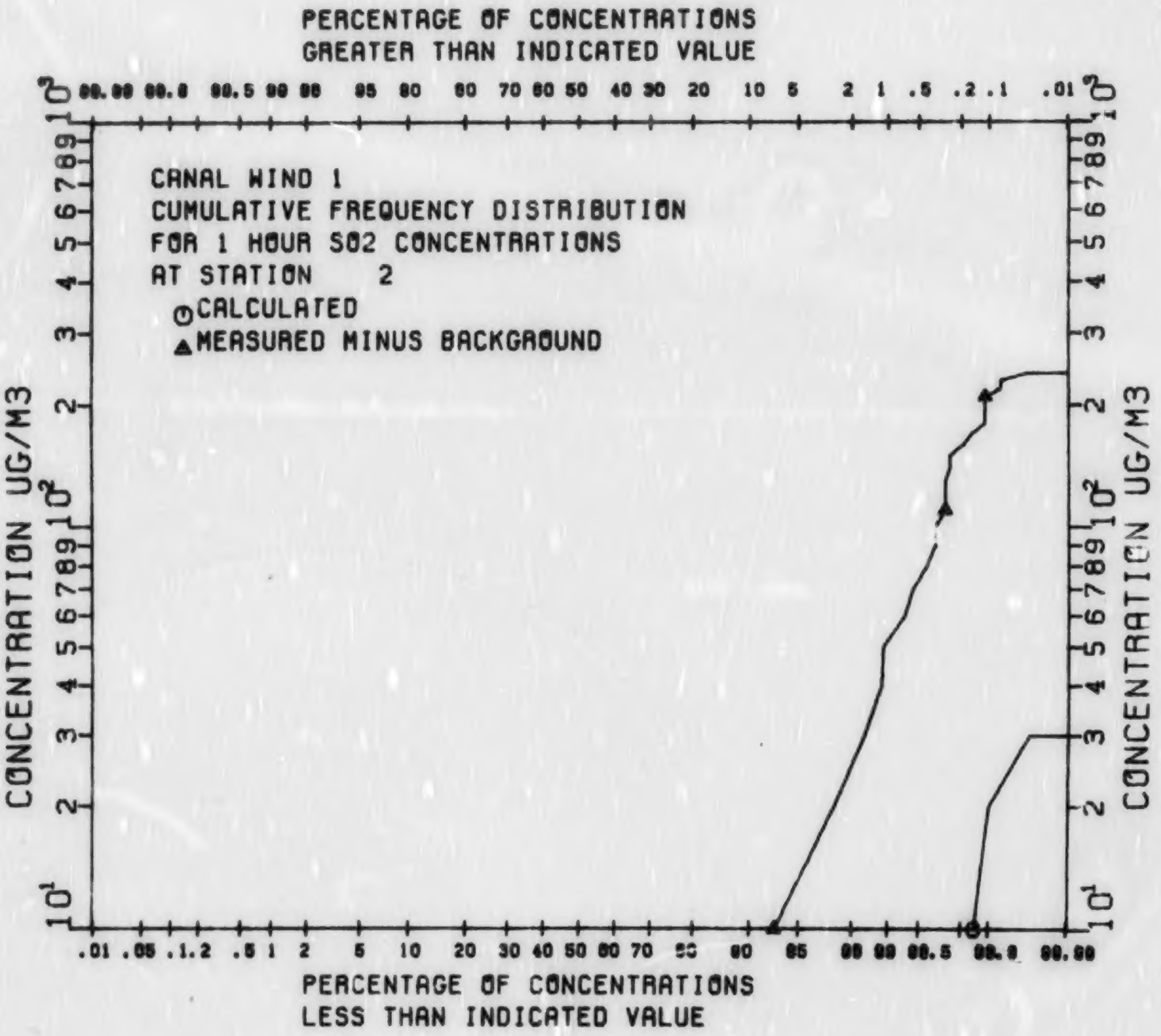

Figure A-19b. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 2 for wind speed class 1 (0 to 2.6 m/sec)

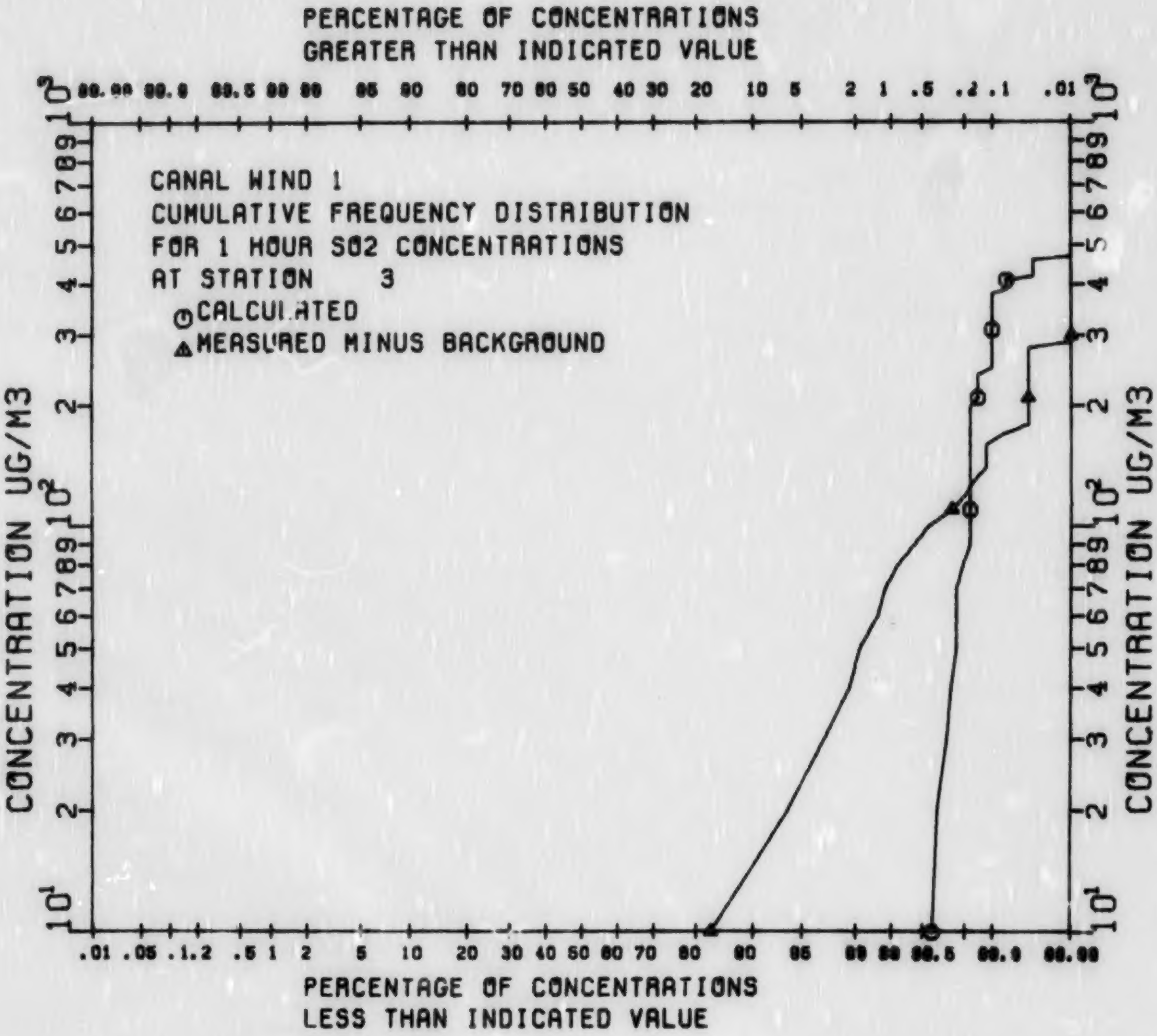

Figure A-19c. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 3 for wind speed class 1 (0 to 2.6 m/sec)

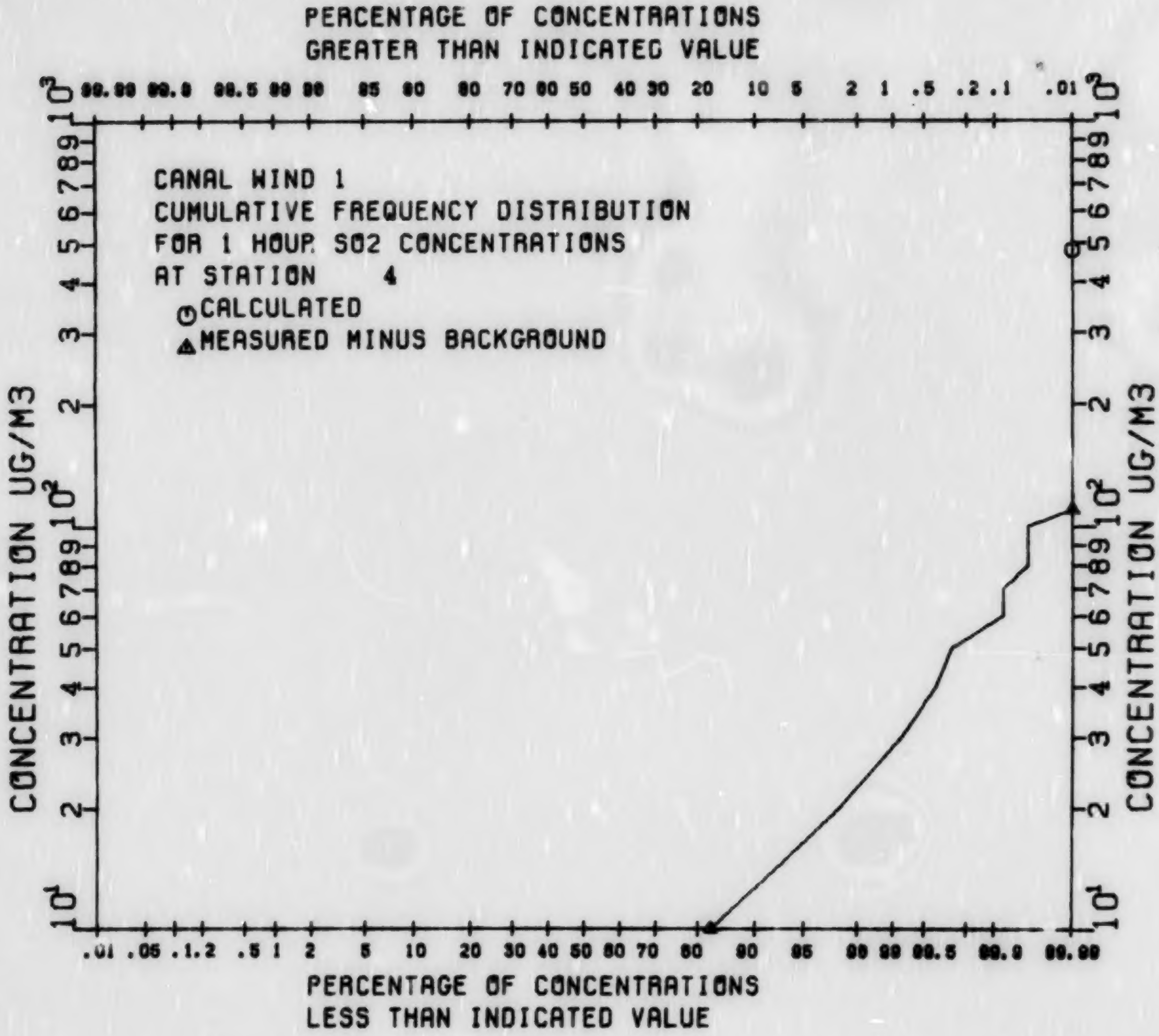

Figure A-19d. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 4 for wind speed class 1 (0 to 2.6 m/sec)

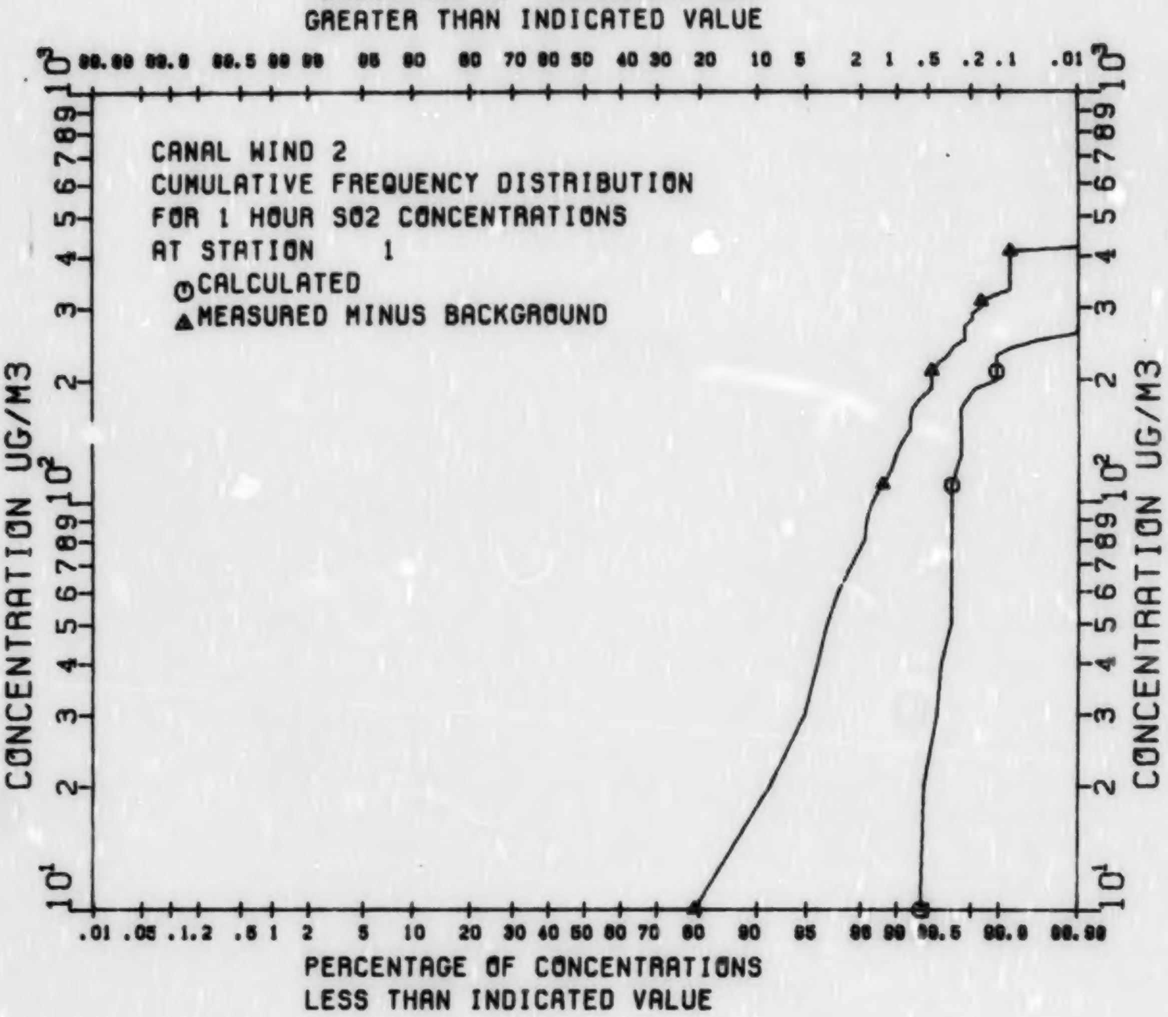

Figure A-20a. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 1 for wind speed class 2 (2.6 to 4.0 m/sec)

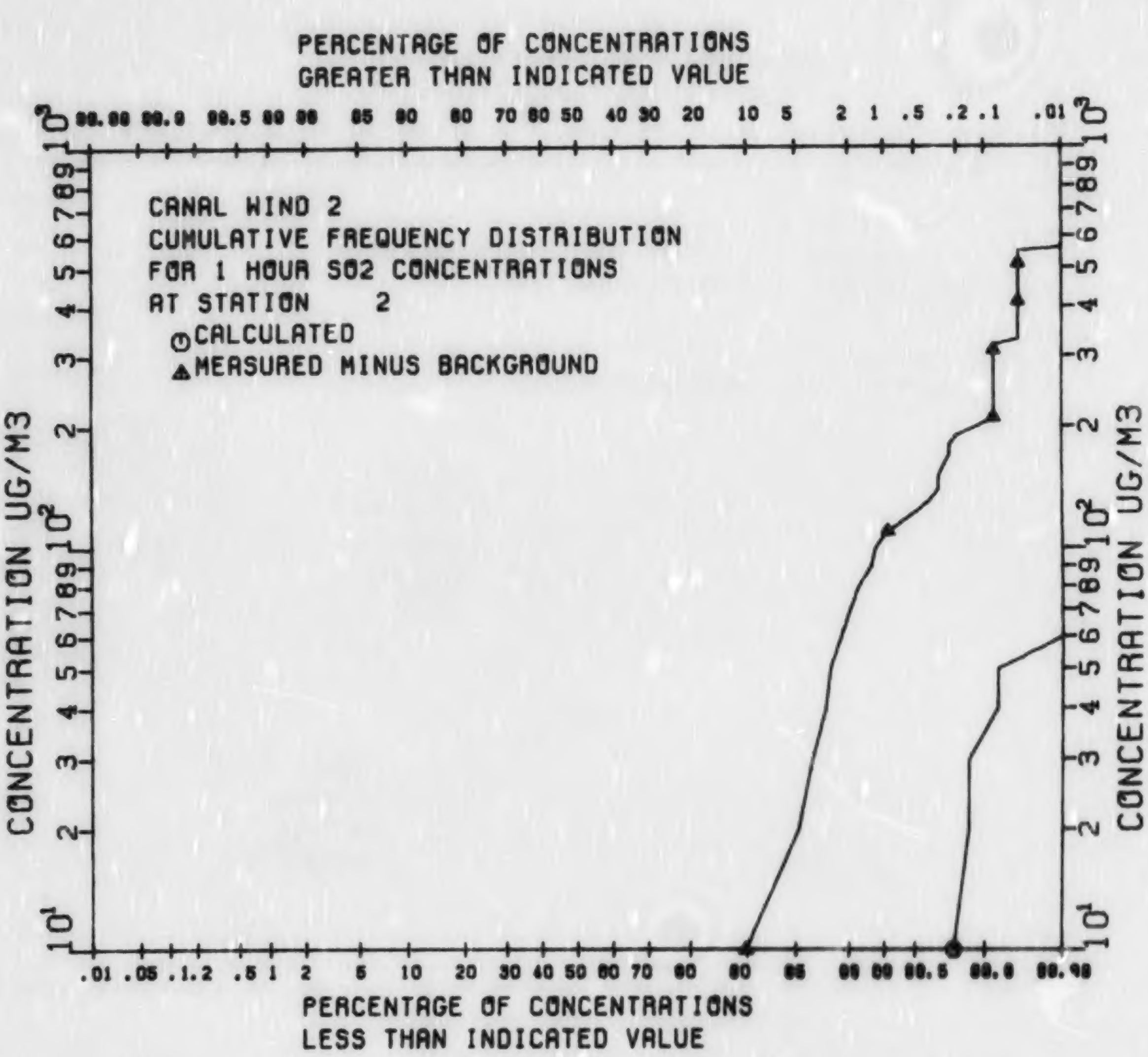

Figure A-20b. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 2 for wind speed class 2 (2.6 to 4.0 m/sec)

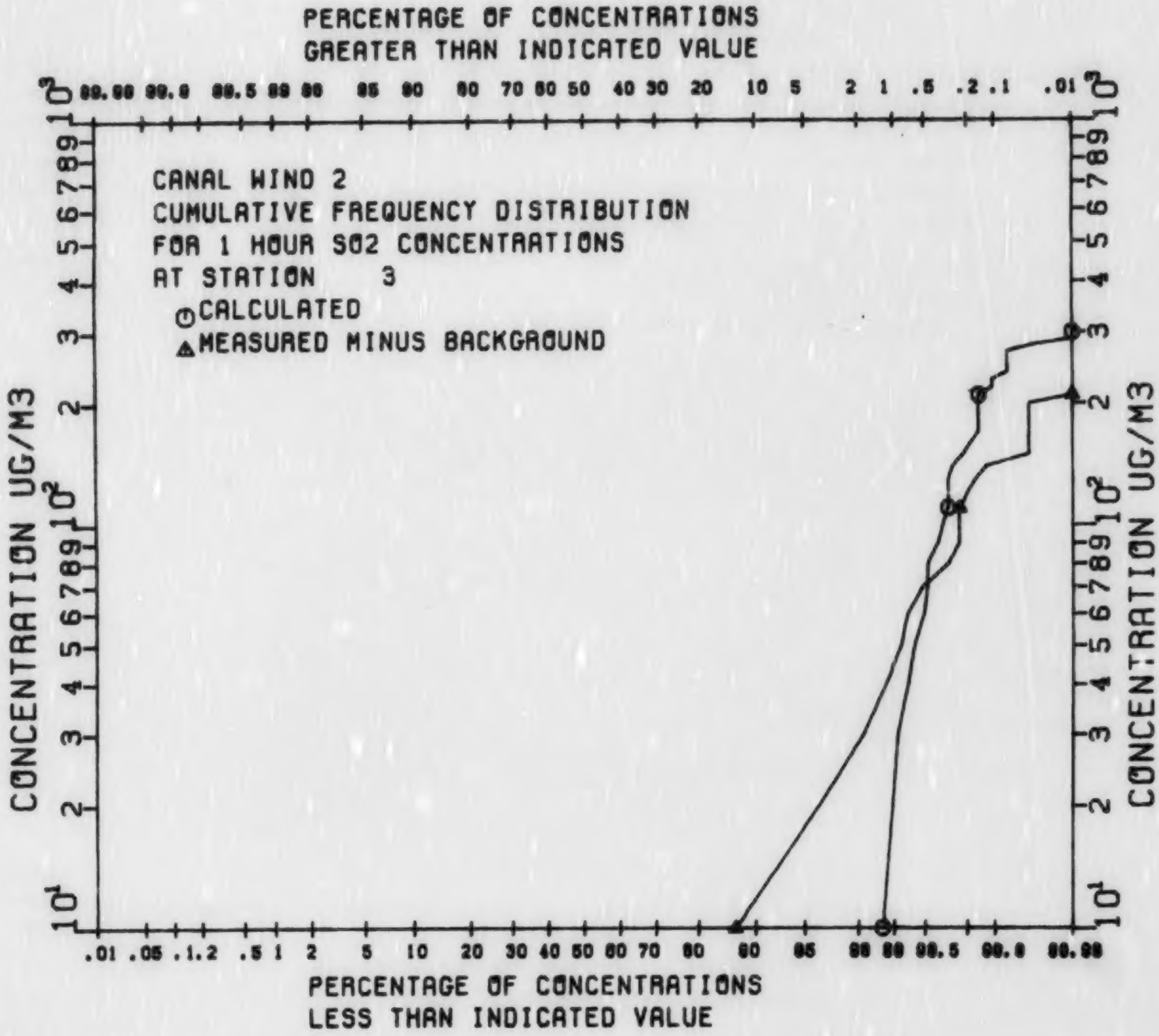

Figure A-20c. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 3 for wind speed class 2 (2.6 to 4.0 m/sec)

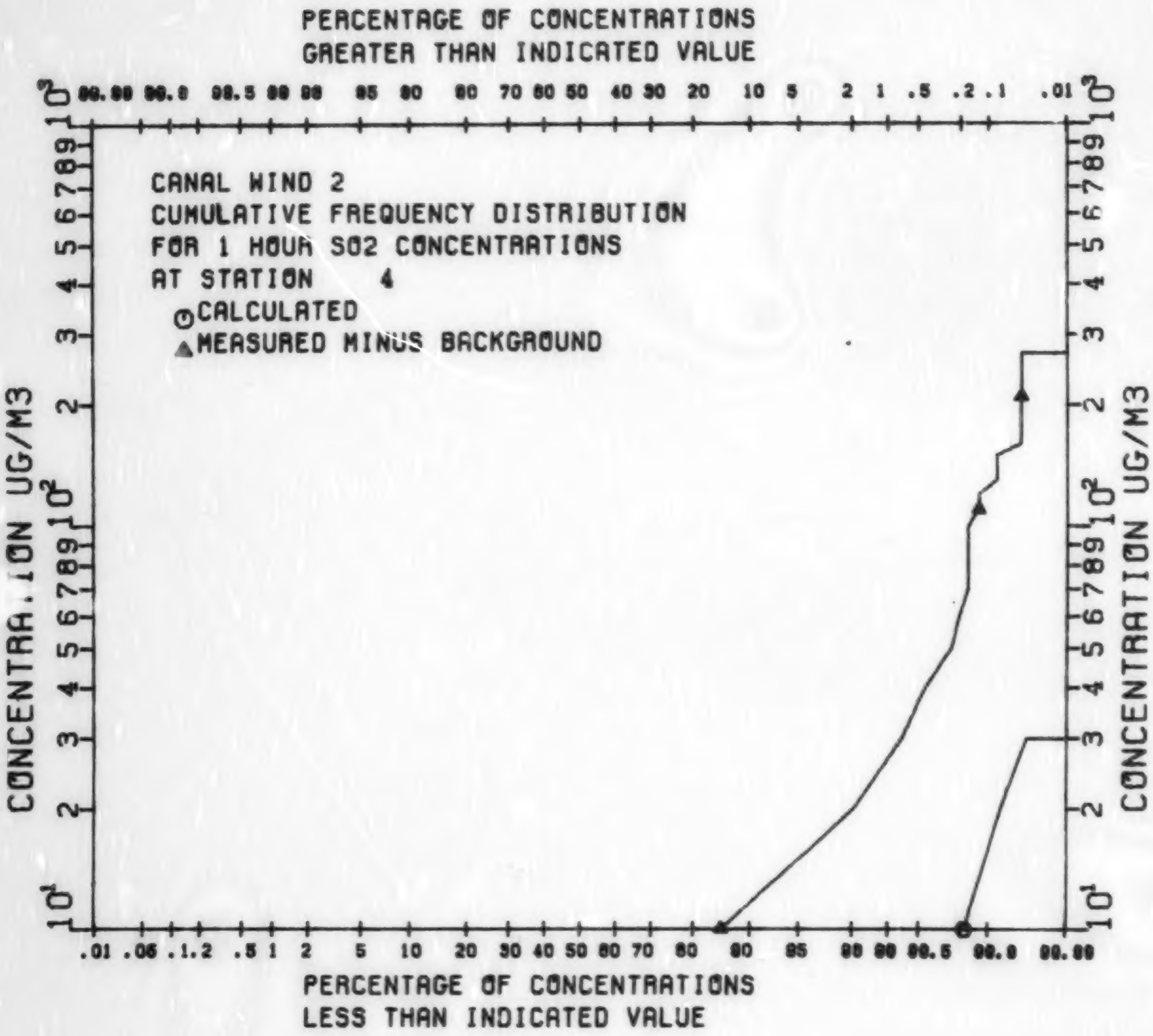

Figure A-20d. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 4 for wind speed class 2 (2.6 to 4.0 m/sec)

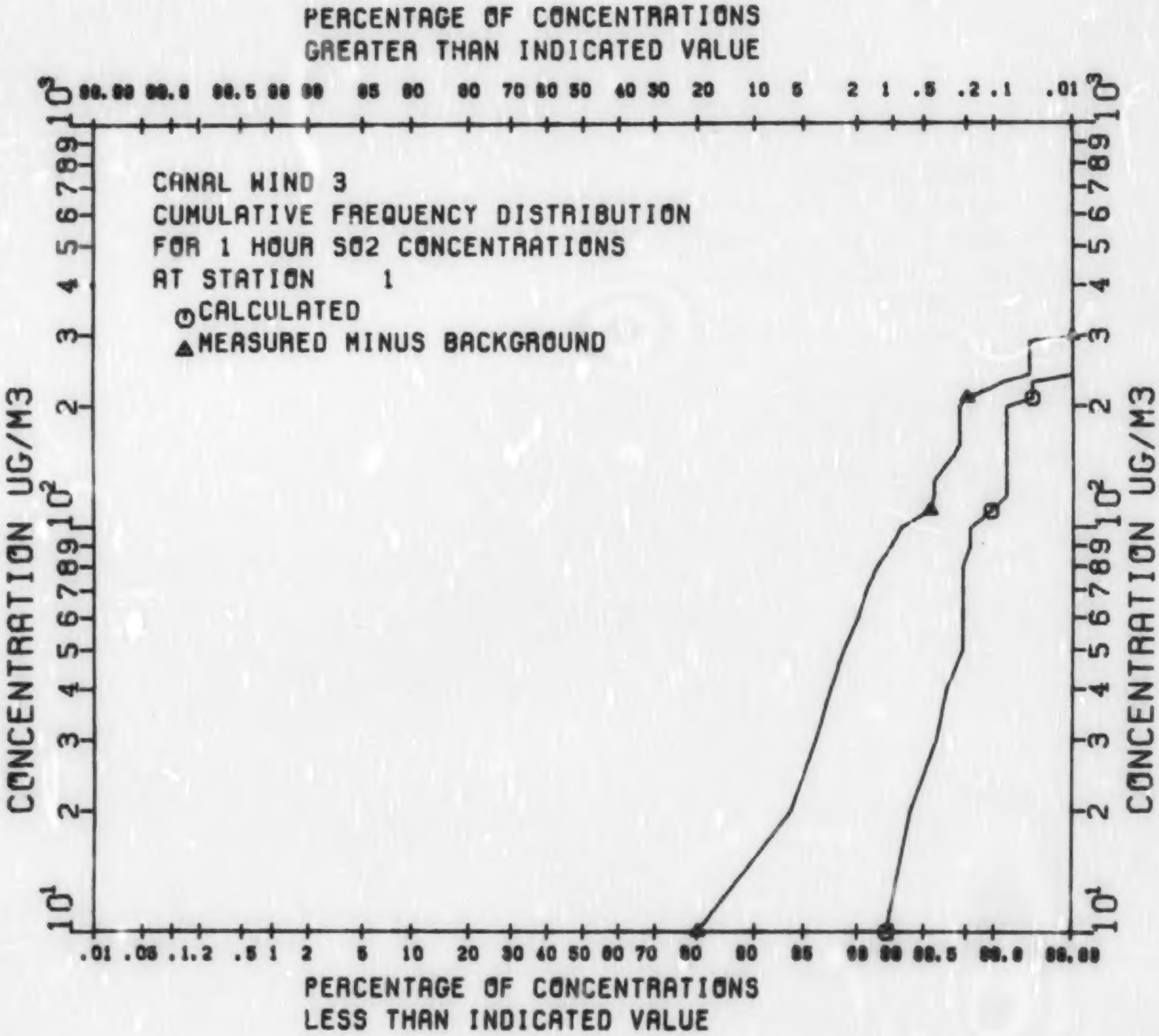

Figure A-21a. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 1 for wind speed class 3 (4.0 m/sec →)

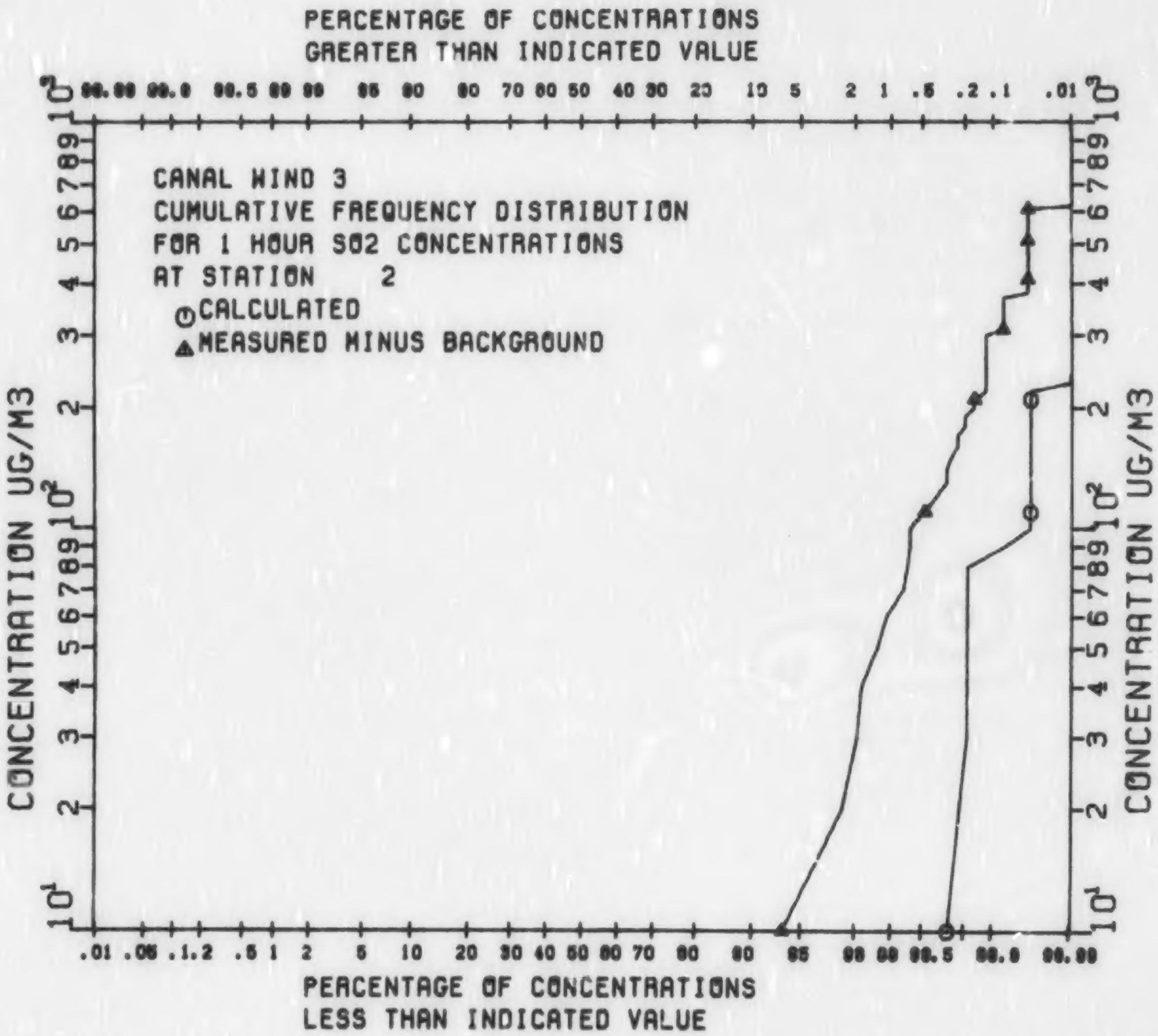

Figure A-21b. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 2 for wind speed class 3 (4.0 m/sec +)

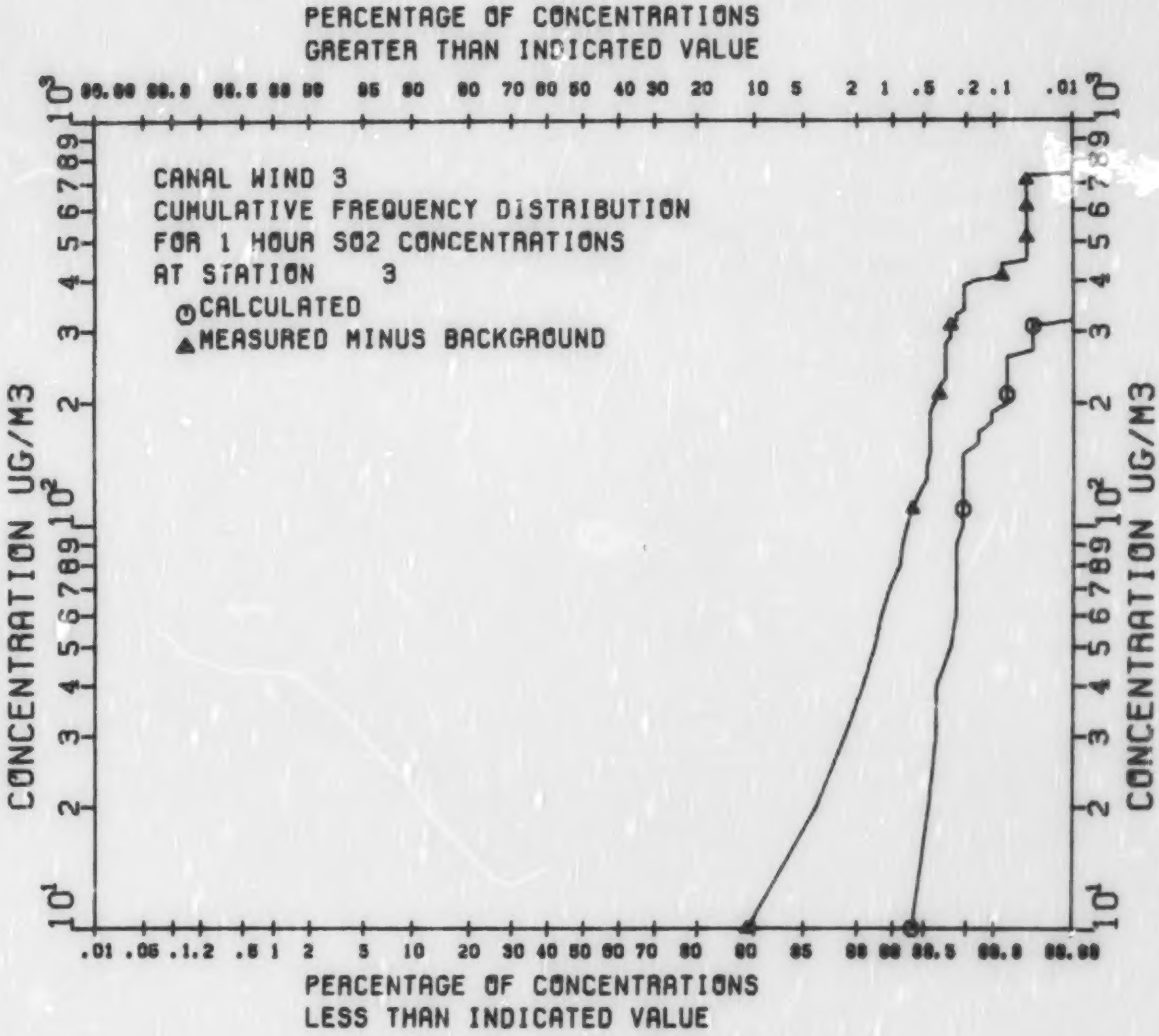

Figure A-21c. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 3 for wind speed class 3 (4.0 m/sec →)

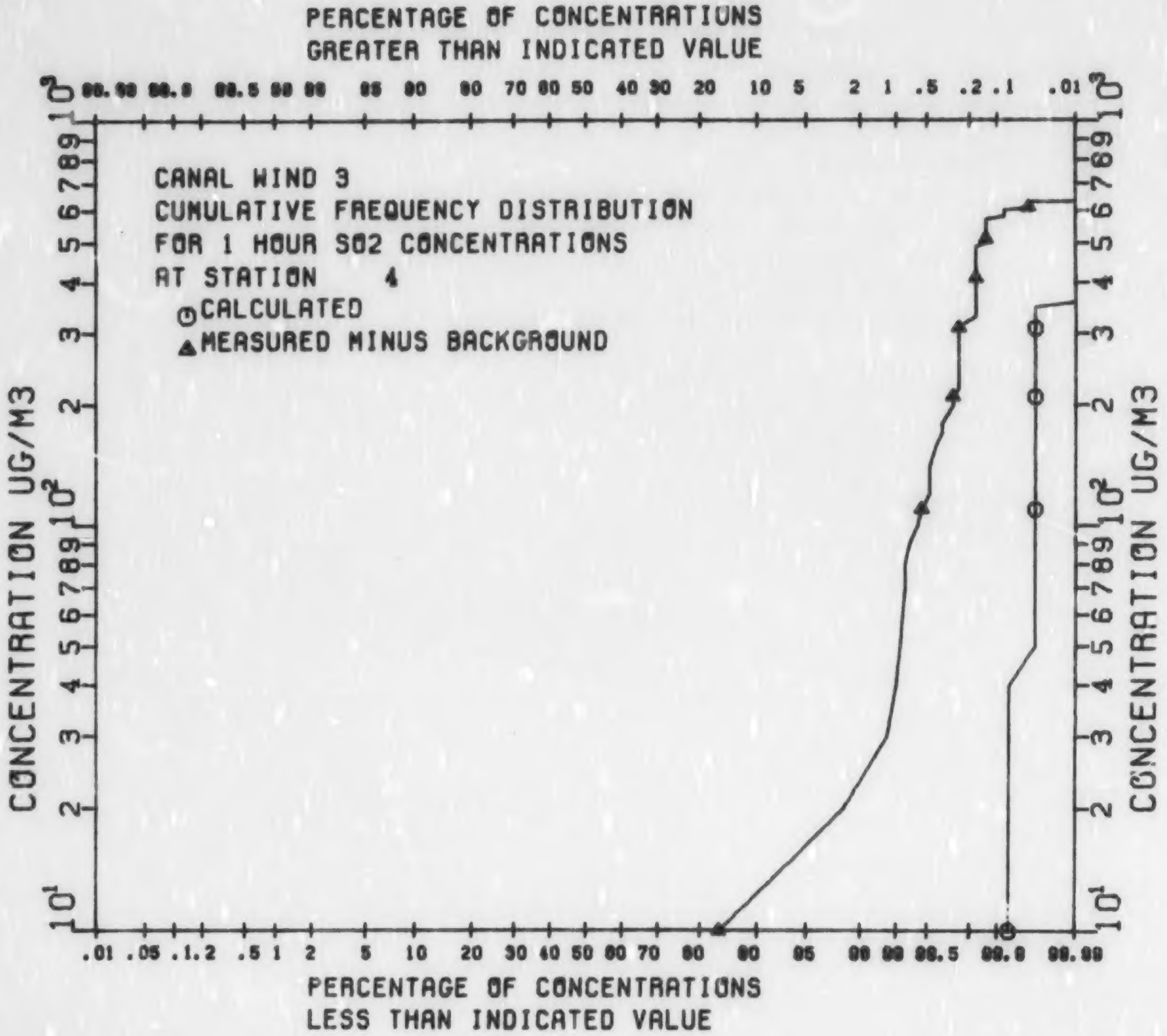

Figure A-21d. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 4 for wind speed class 3 (4.0 m/sec →)

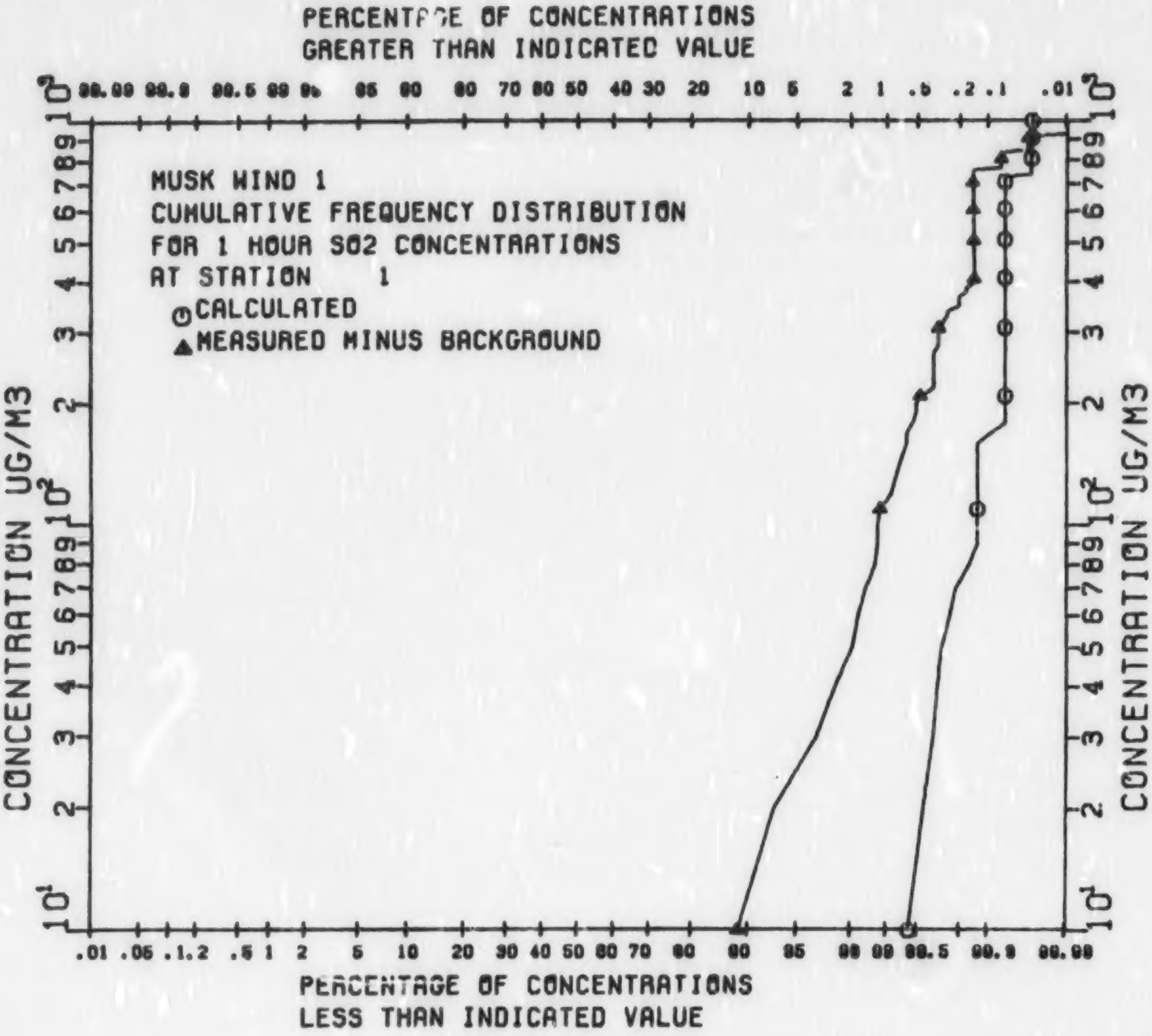

Figure A-22a. Cumulative frequency distributions of calcualted concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 1 for wind speed class 1 (0 to 1.6 m/sec)

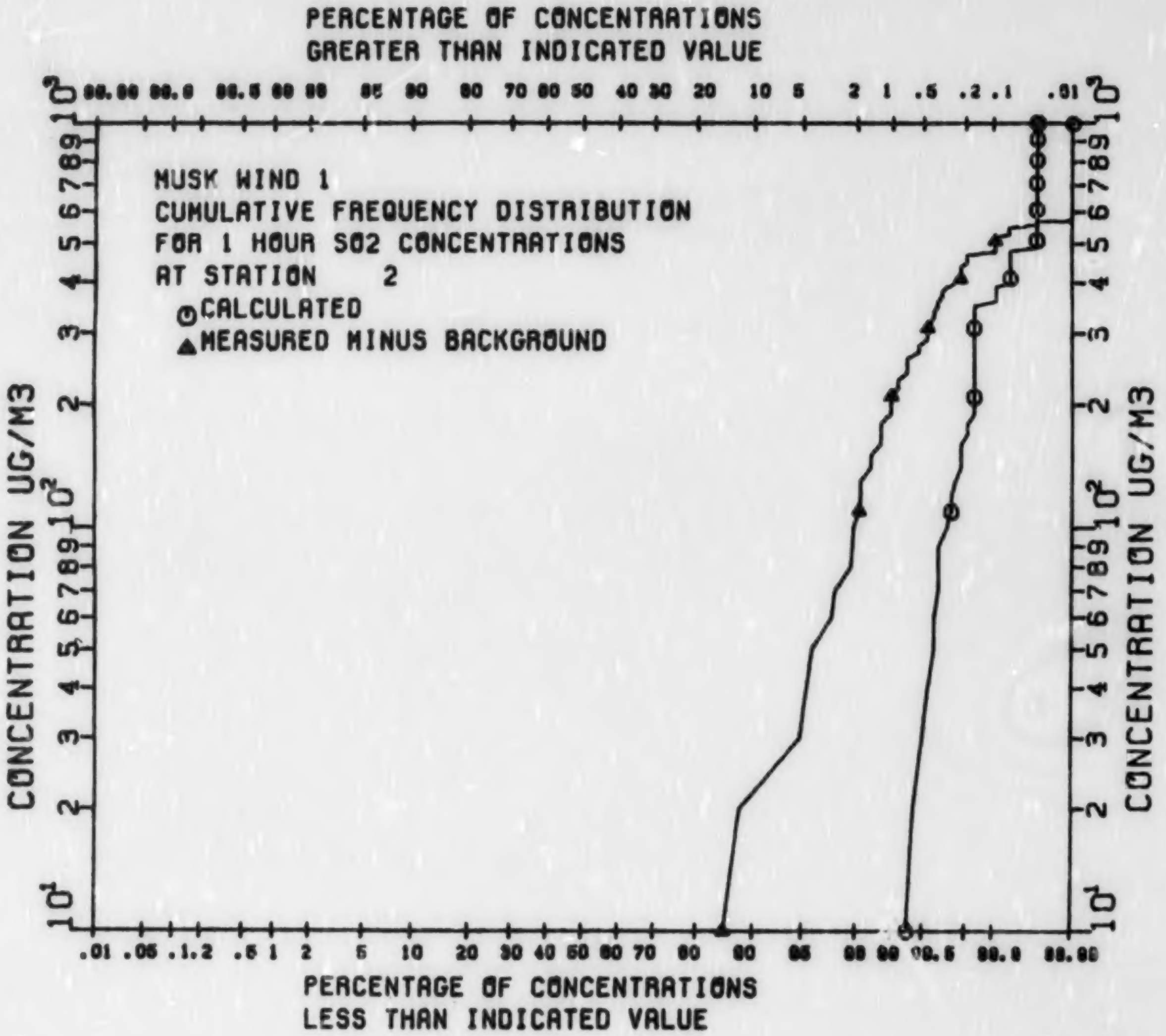

Figure A-22b. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 2 for wind speed class 1 (0 to 1.6 m/sec)

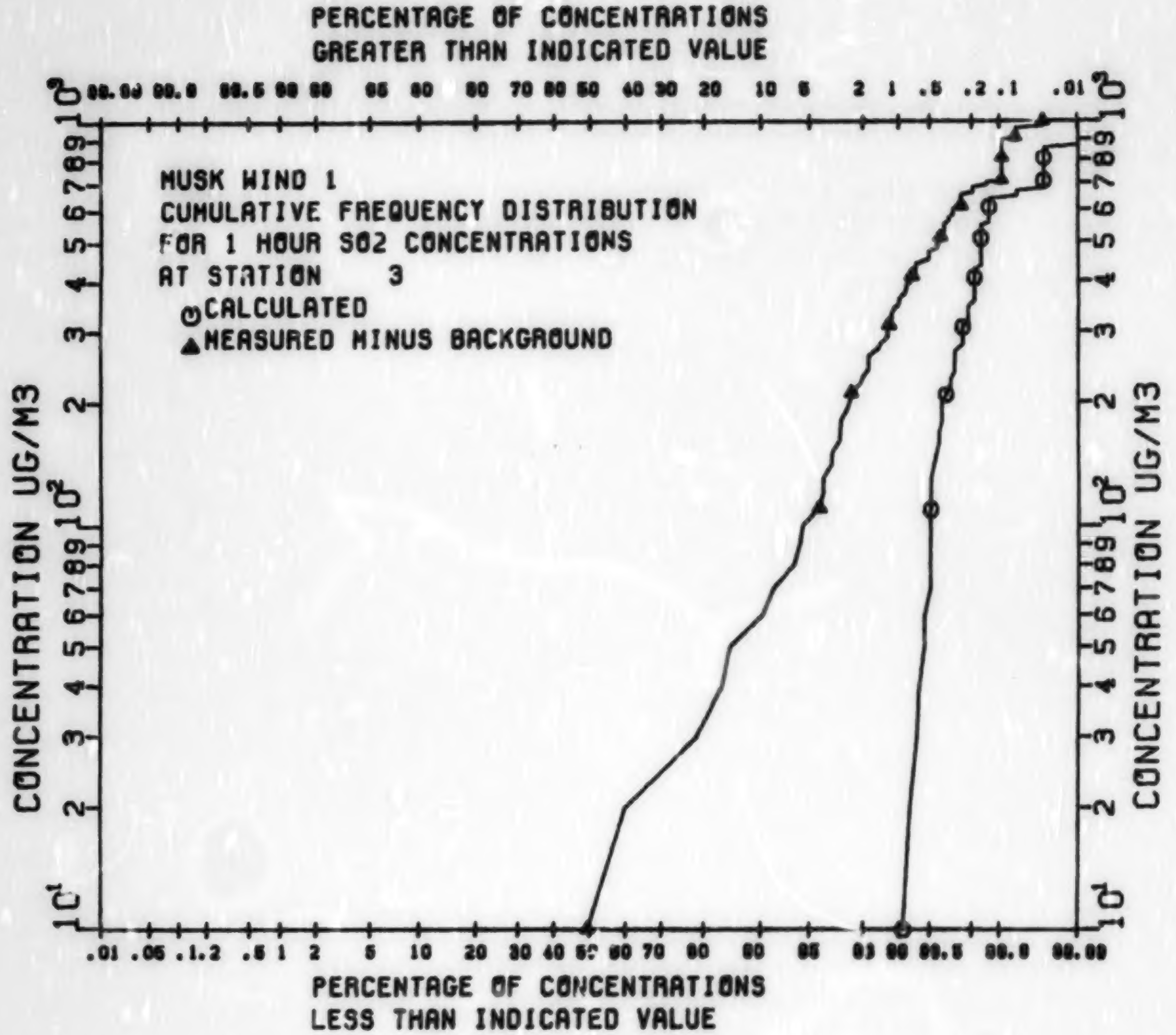

Figure A-22c. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 3 for wind speed class 1 (0 to 1.6 m/sec)

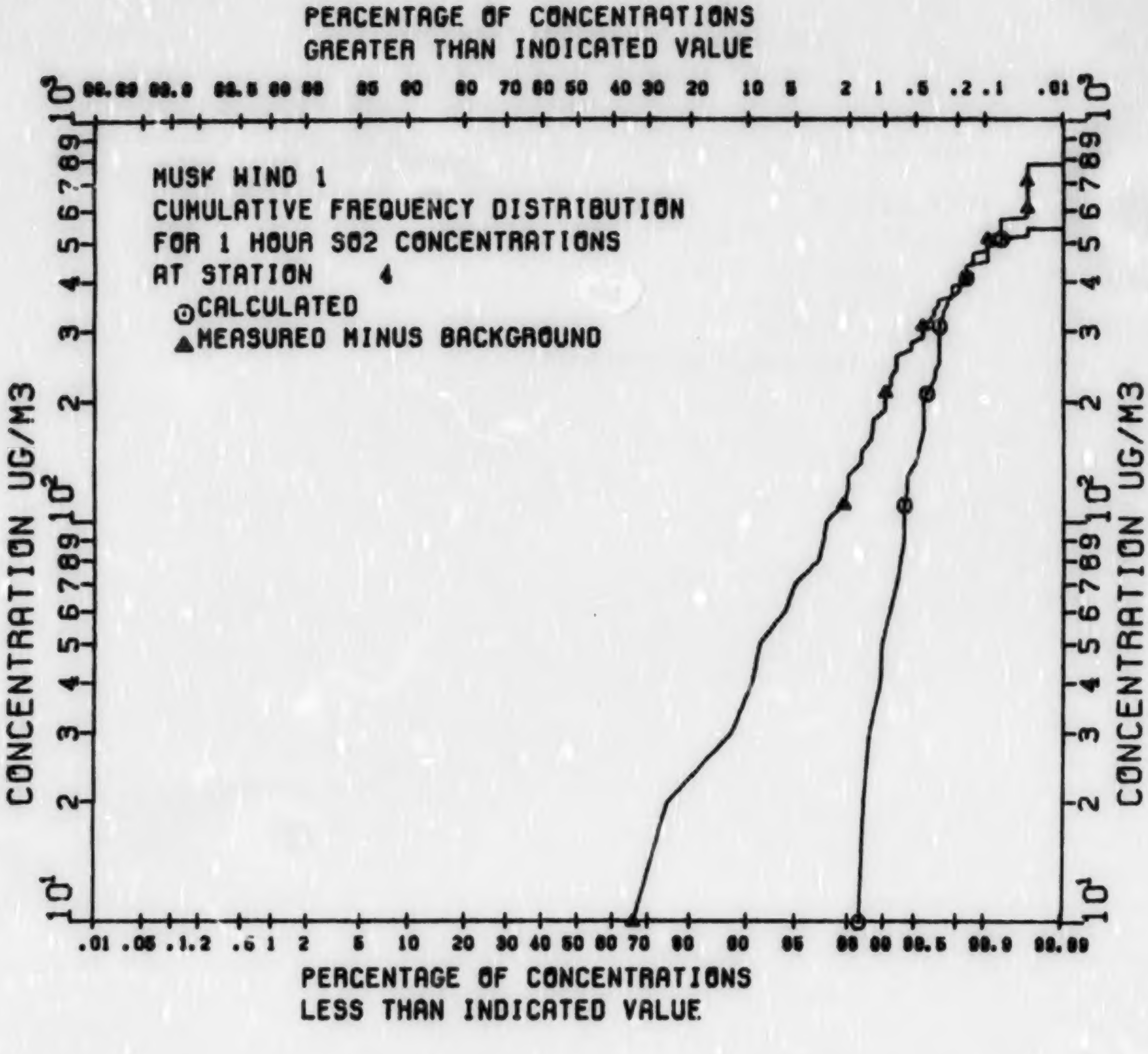

Figure A-22d. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 4 for wind speed class 1 (0 to 1.6 m/sec)

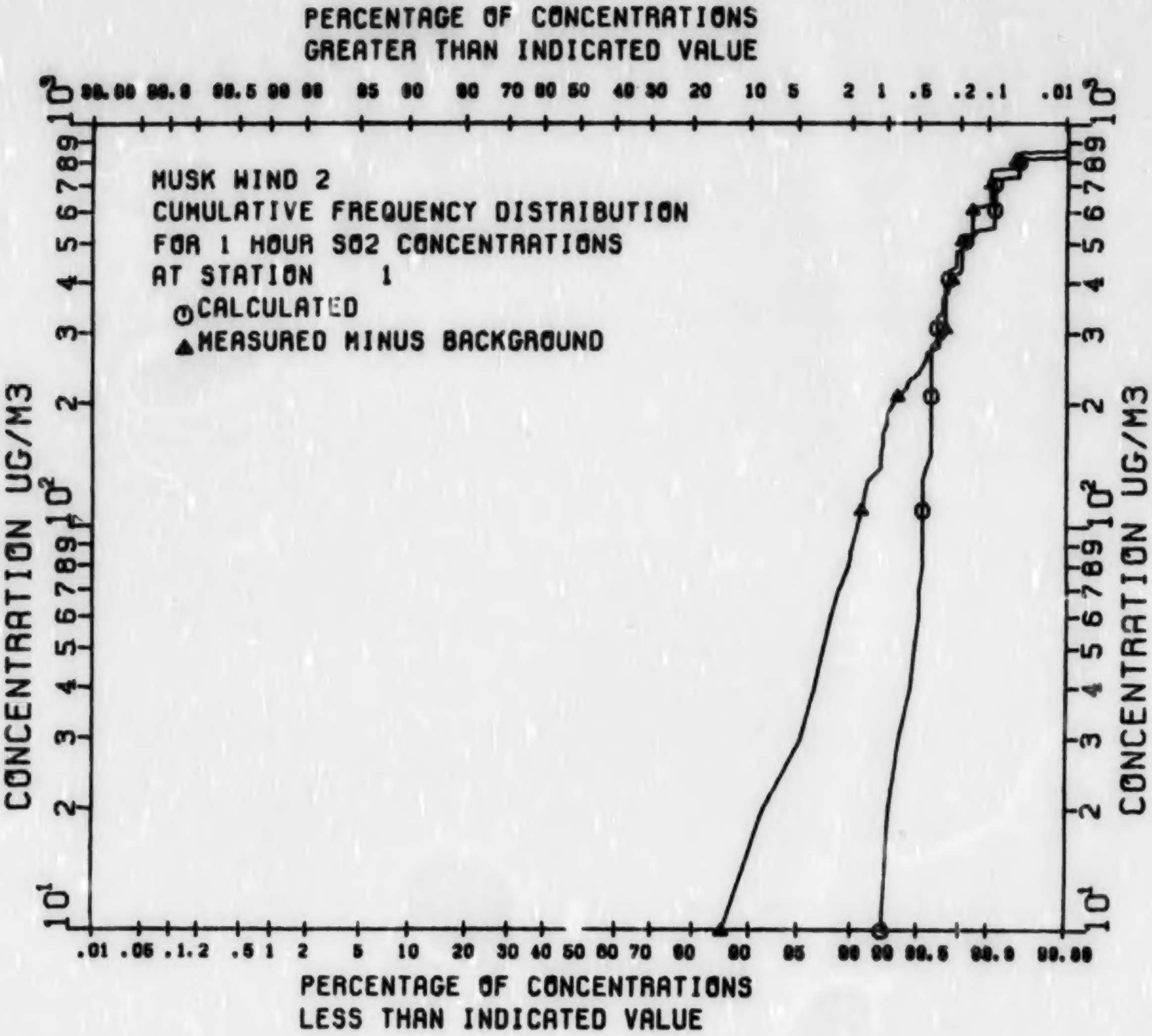

Figure A-23a. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 1 for wind speed class 2 (1.6 to 2.4 m/sec)

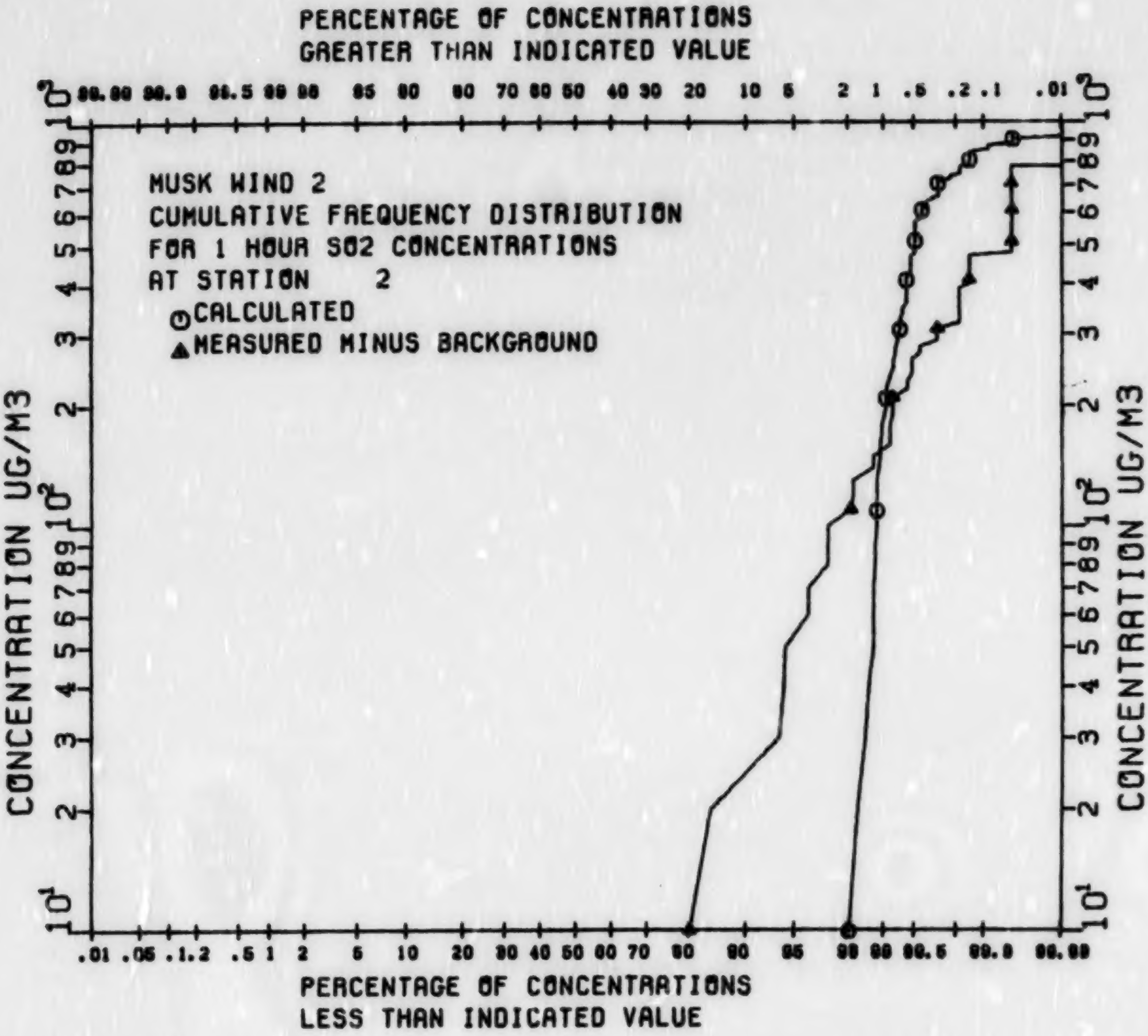

Figure A-23b. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 2 for wind speed class 2 (1.6 to 2.4 m/sec)

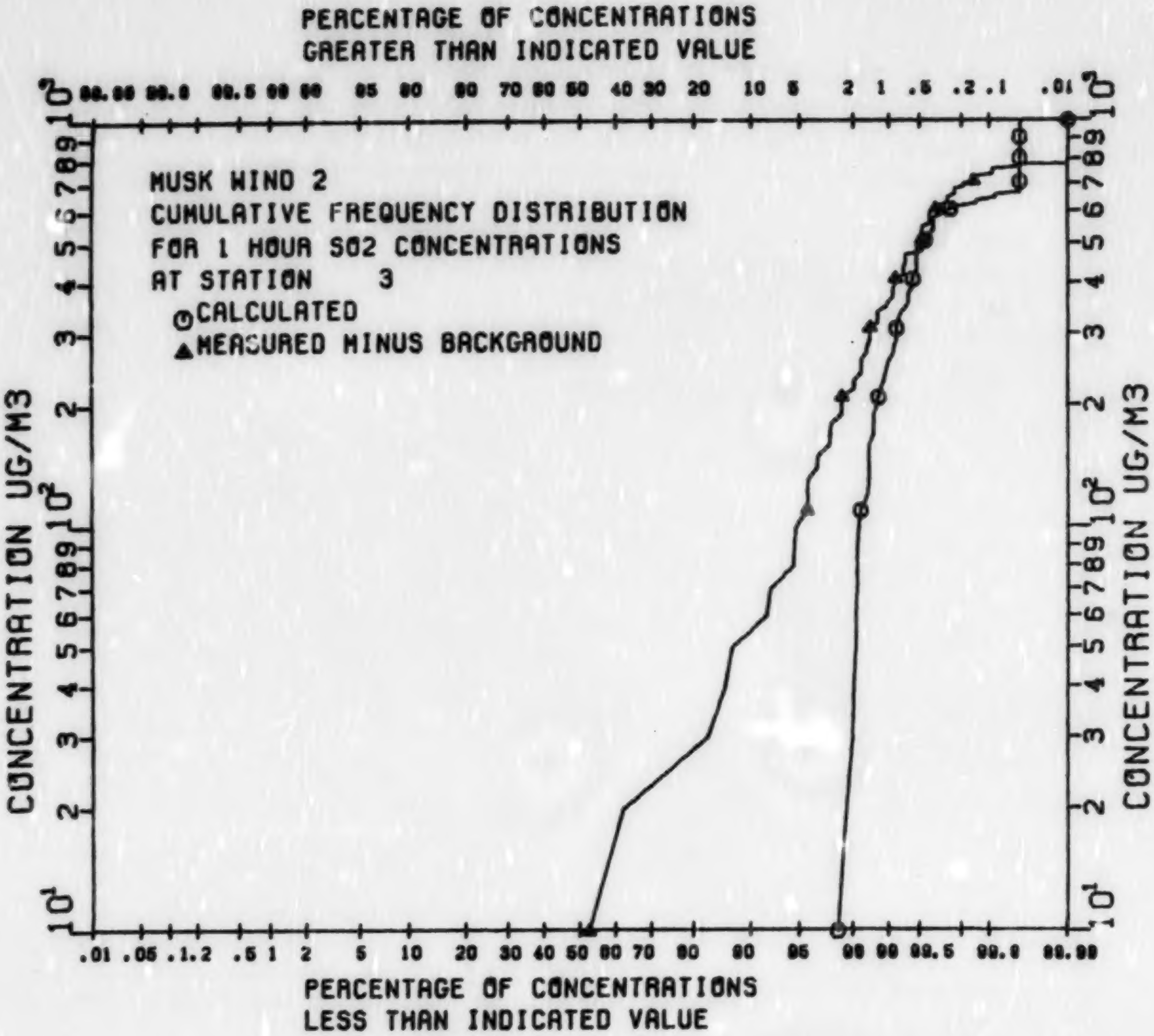

Figure A-23c. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 3 for wind speed class 2 (1.6 to 2.4 m/sec)

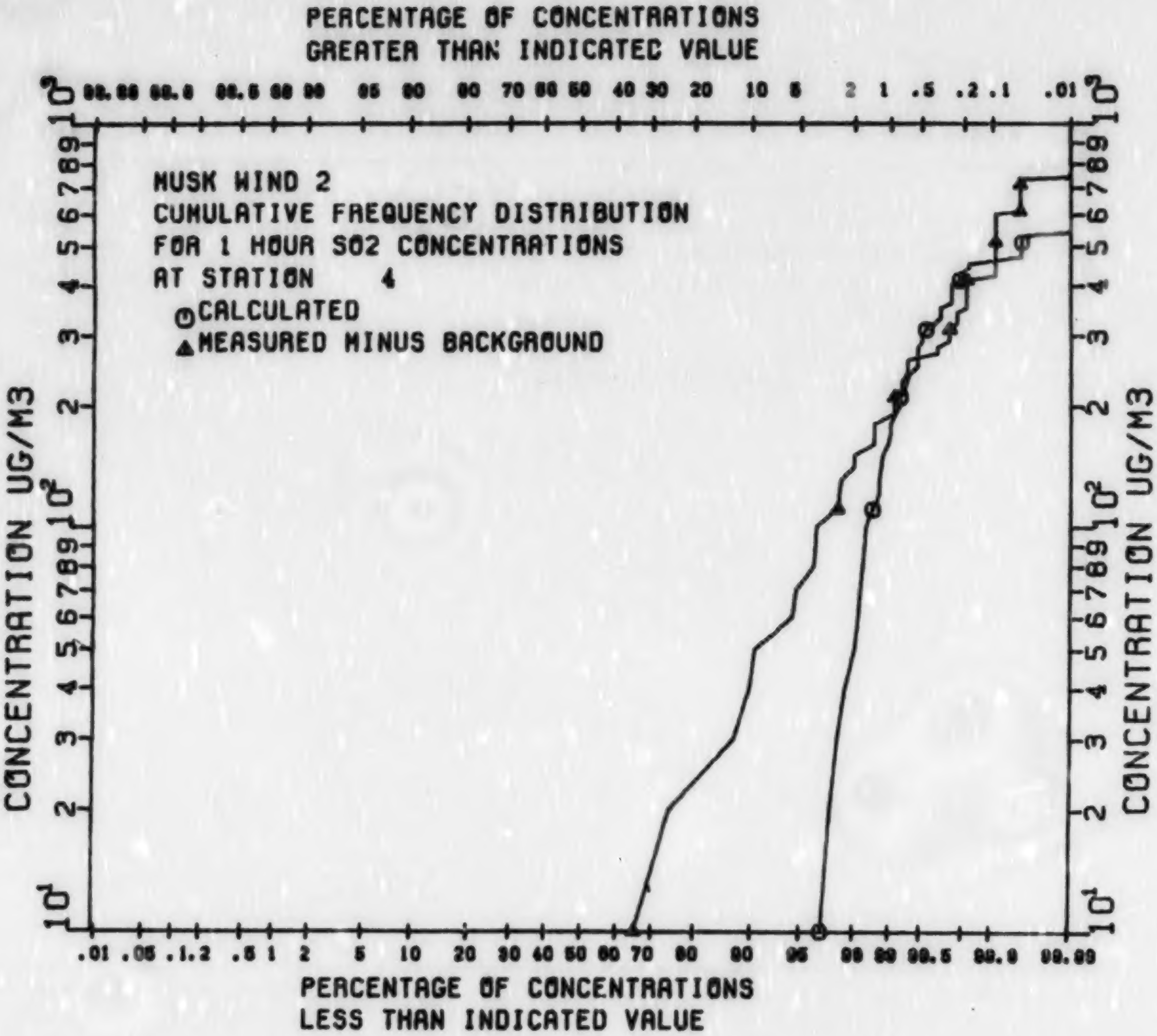

Figure A-23d. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 4 for wind speed class 2 (1.6 to 2.4 m/sec)

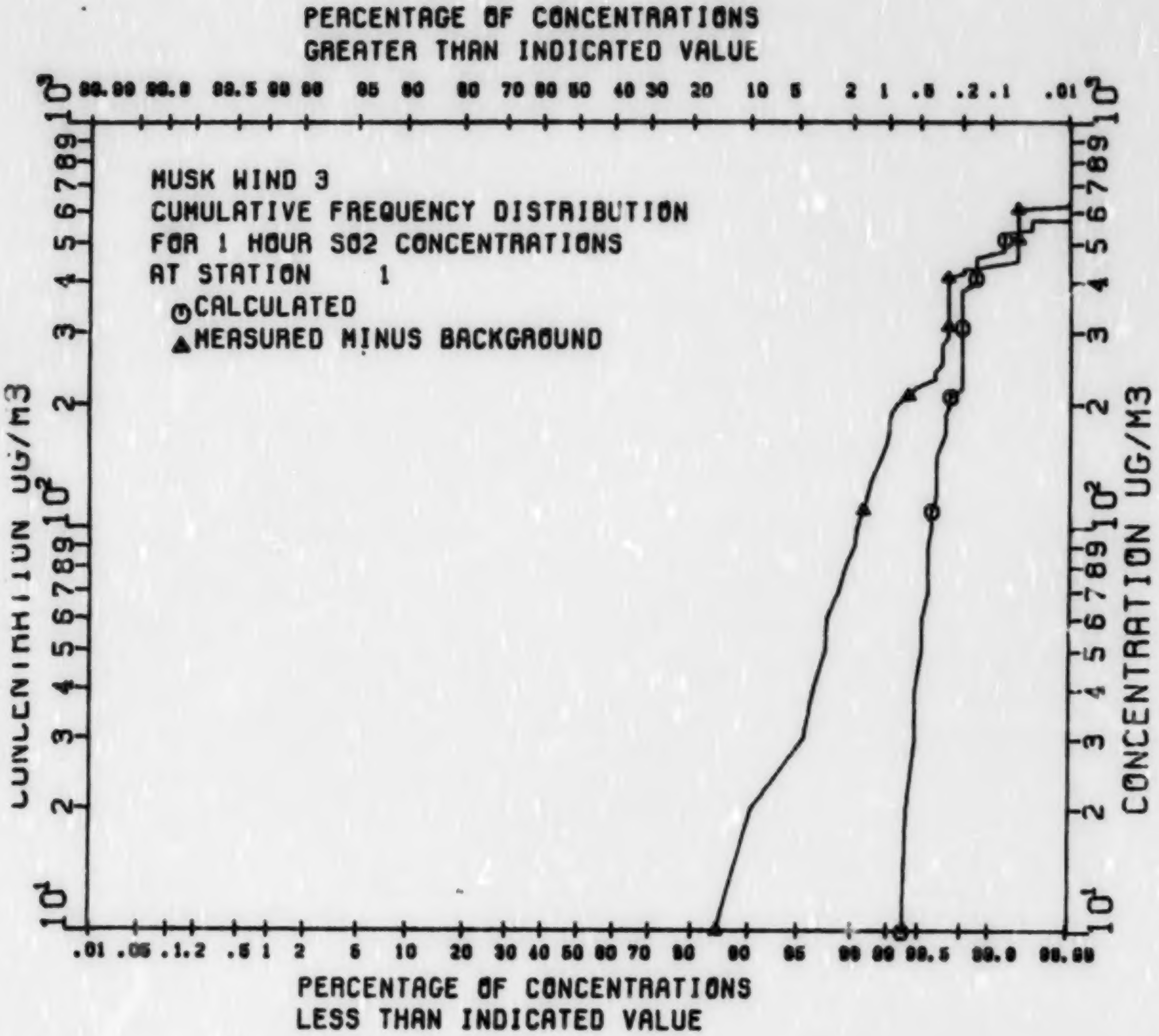

Figure A-24a. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 1 for wind speed class 3 (2.4 m/sec →)

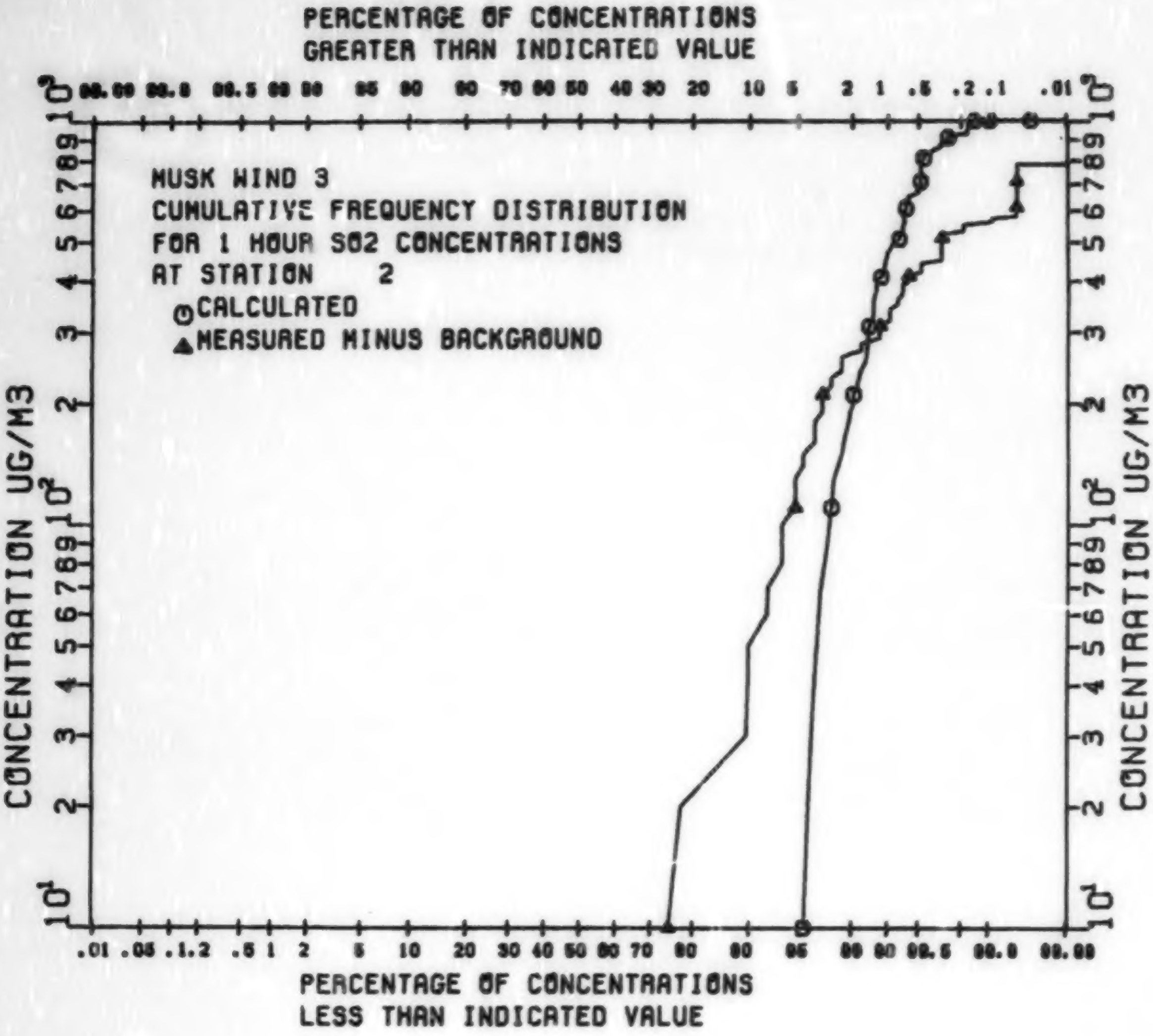

Figure A-24b. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 2 for wind speed class 3 (2.4 m/sec →)

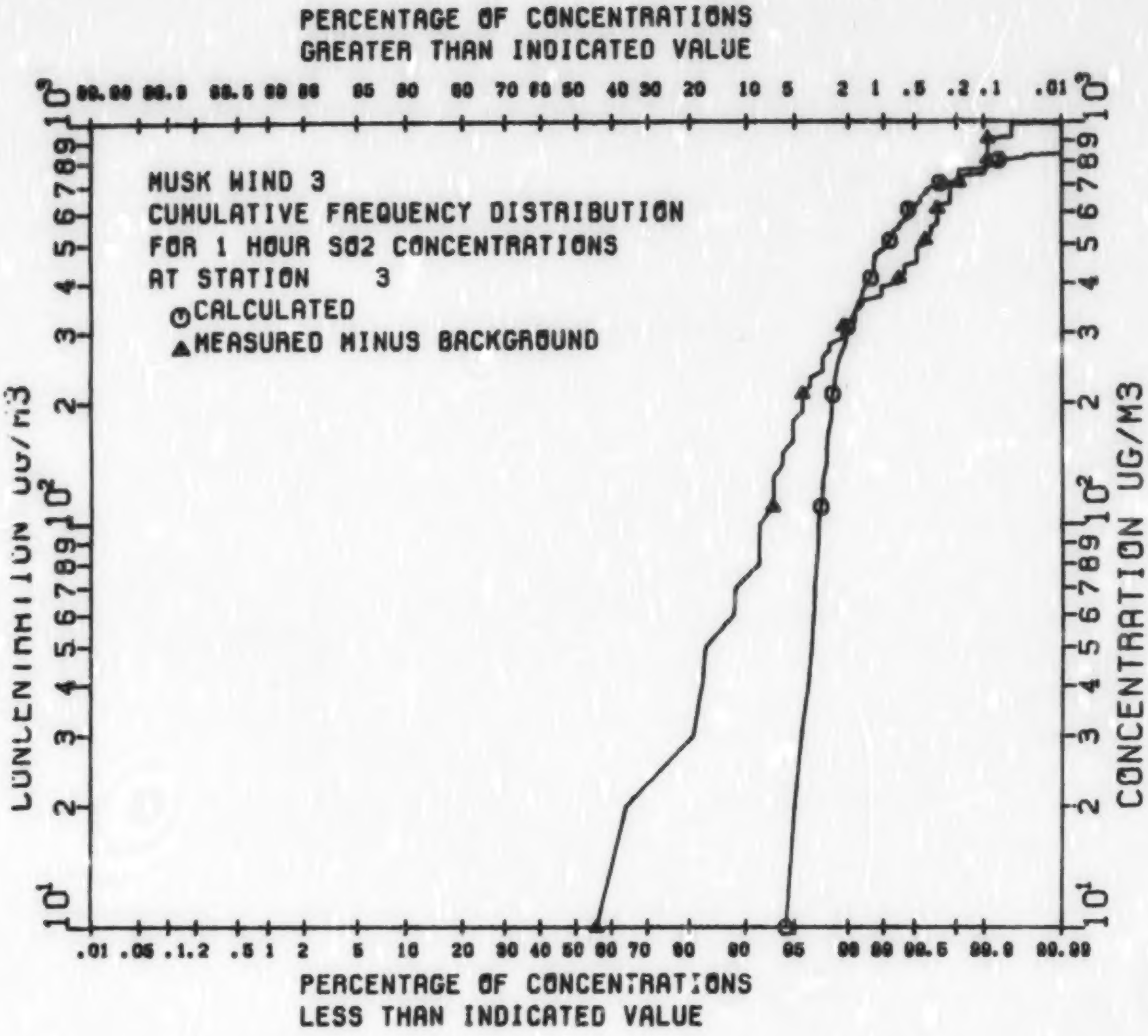

Figure A-24c. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 3 for wind speed class 3 (2.4 m/sec →)

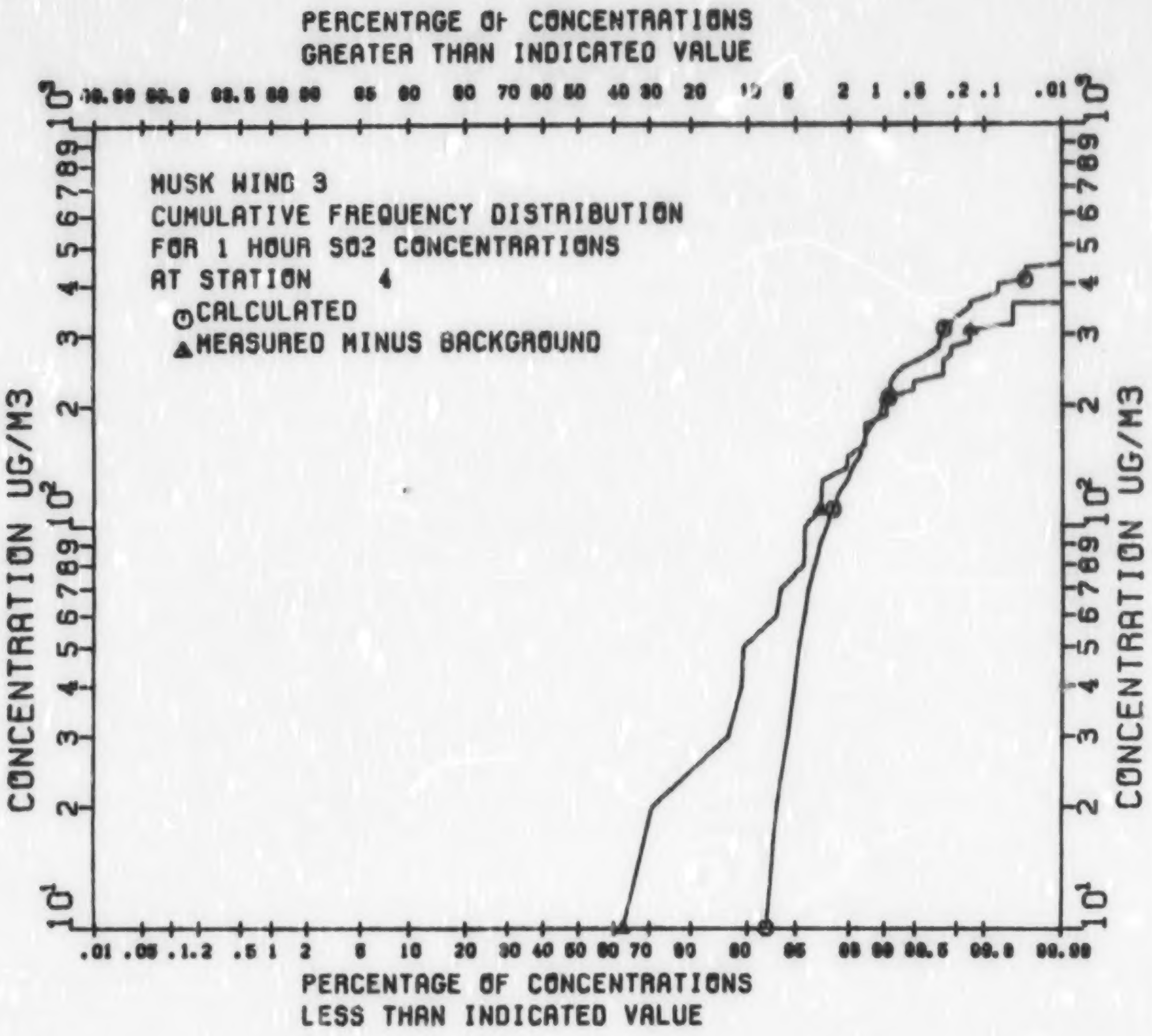

Figure A-24d. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 4 for wind speed class 3 (2.4 m/sec →)

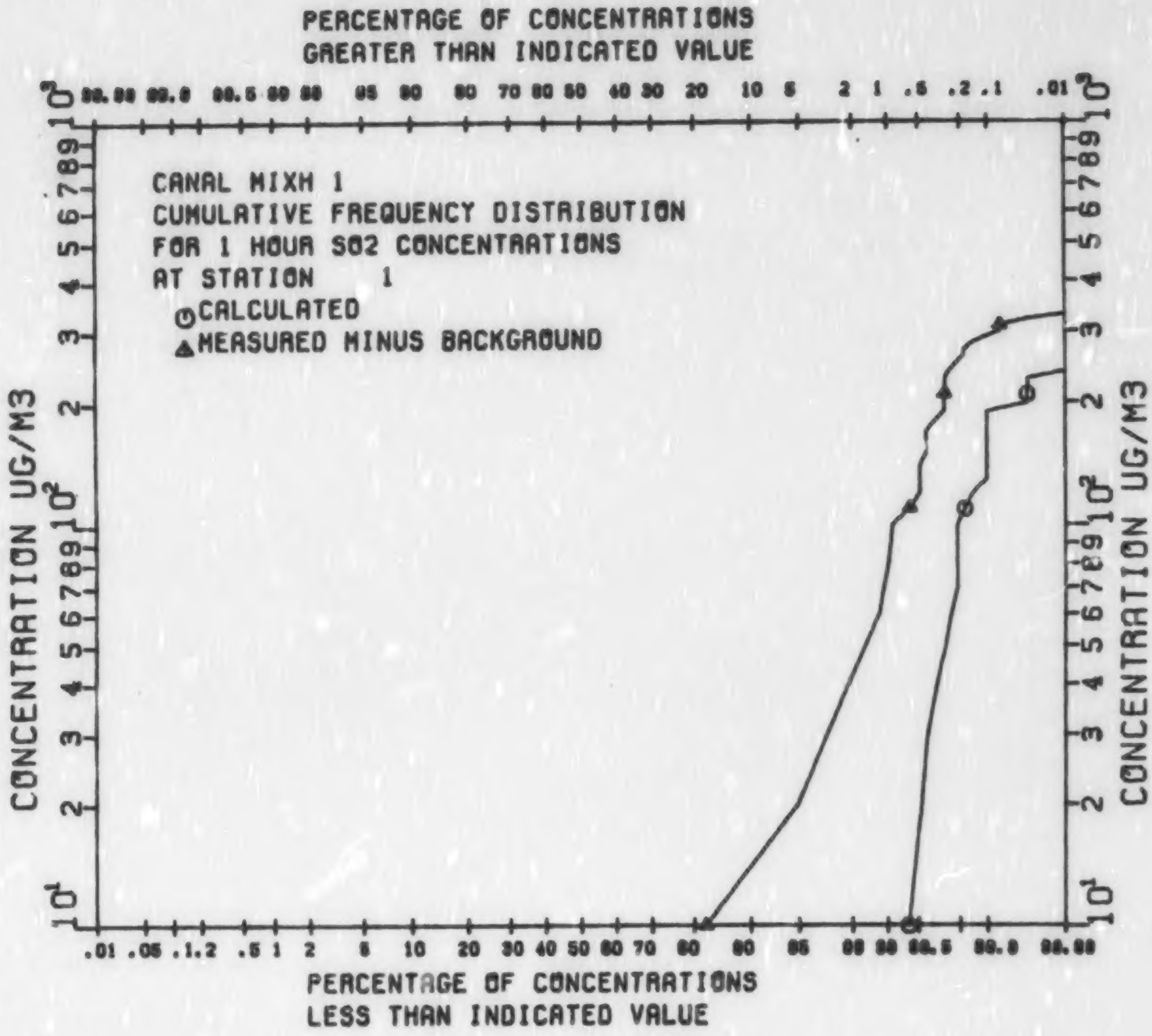

Figure A-25a. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 1 for mixing height class 1 (0 to 750 m)

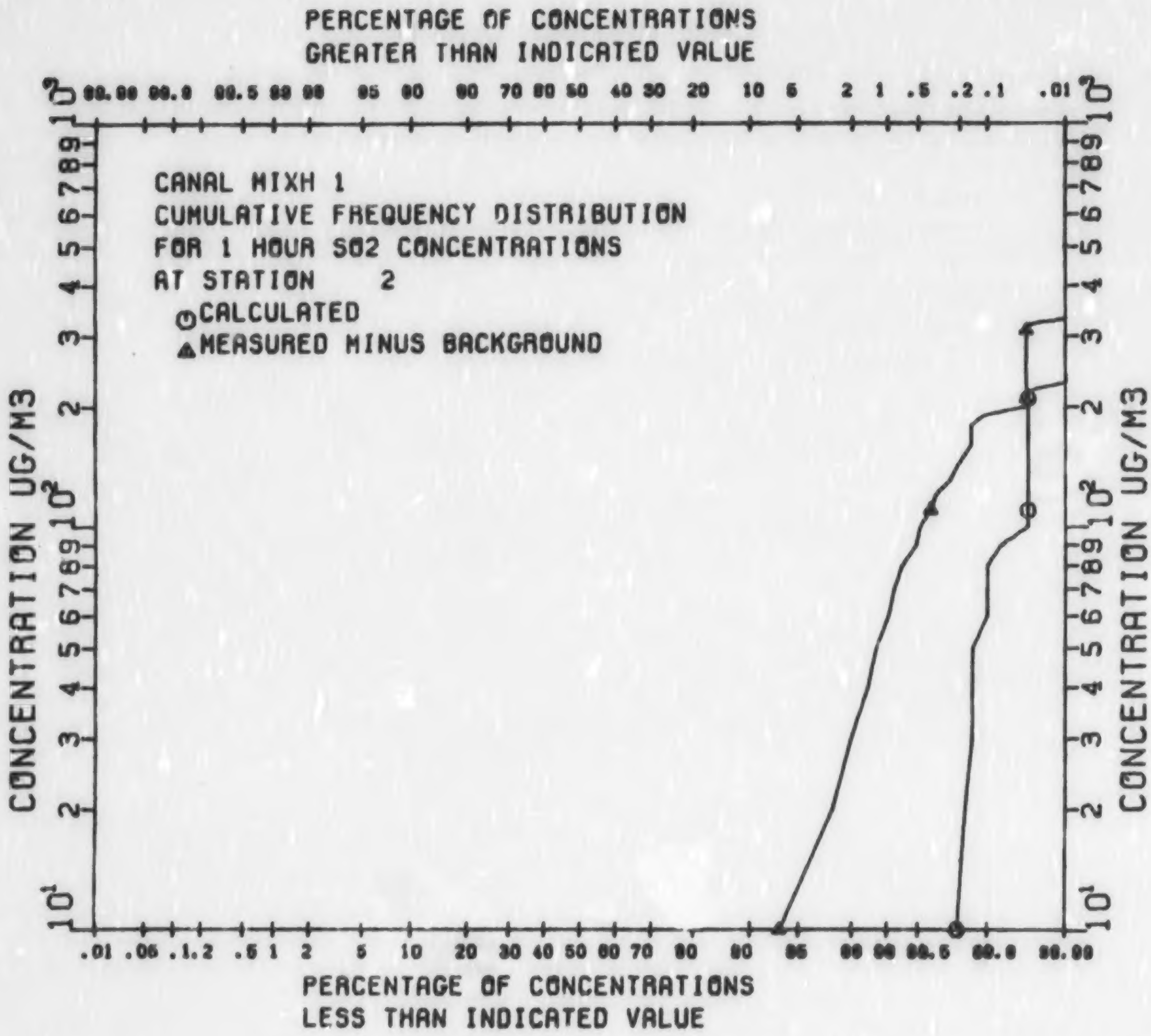

Figure A-25b. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 2 for mixing height class 1 (0 to 750 m)

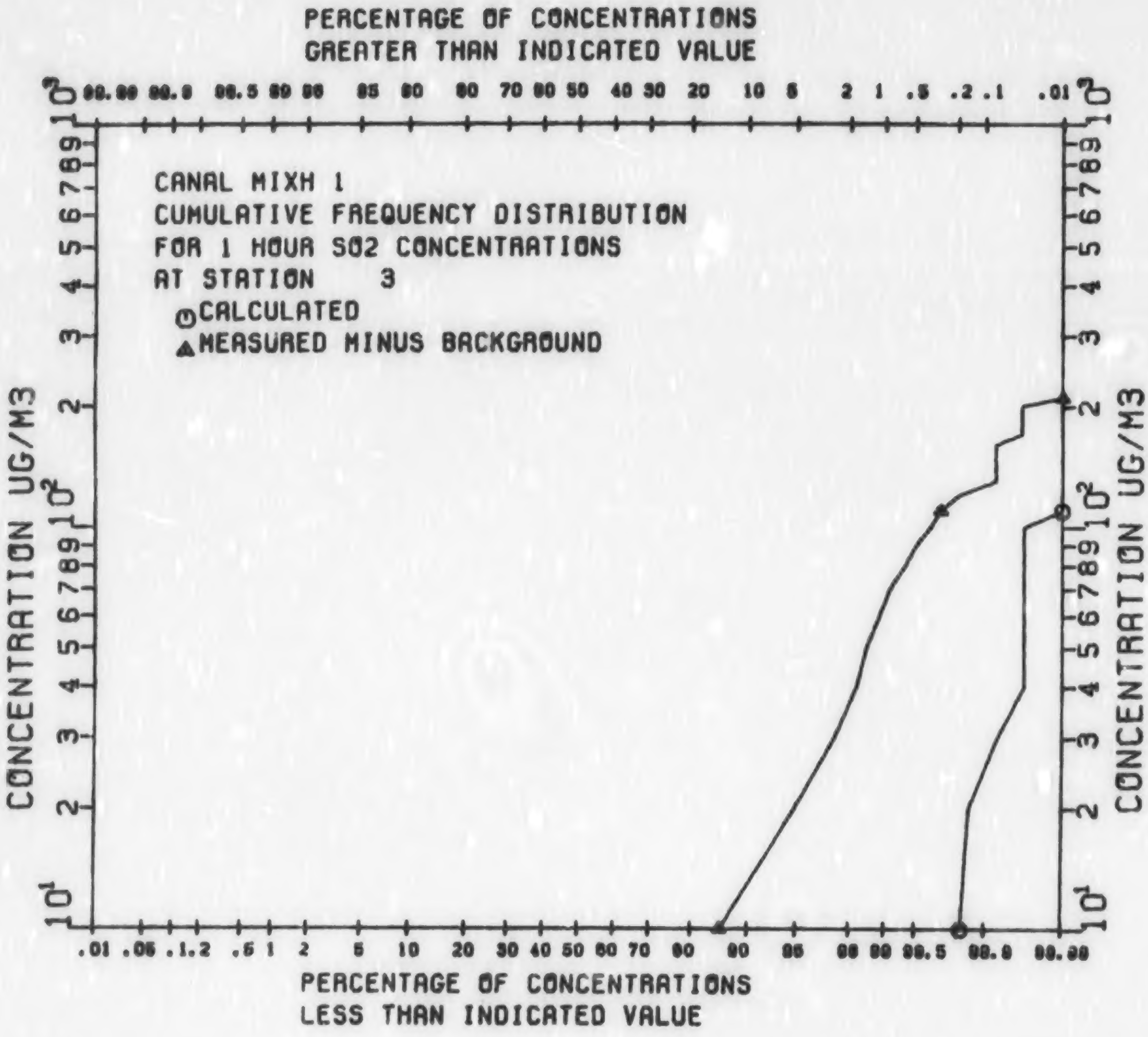

Figure A-25c. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 3 for mixing height class 1 (0 to 750 m)

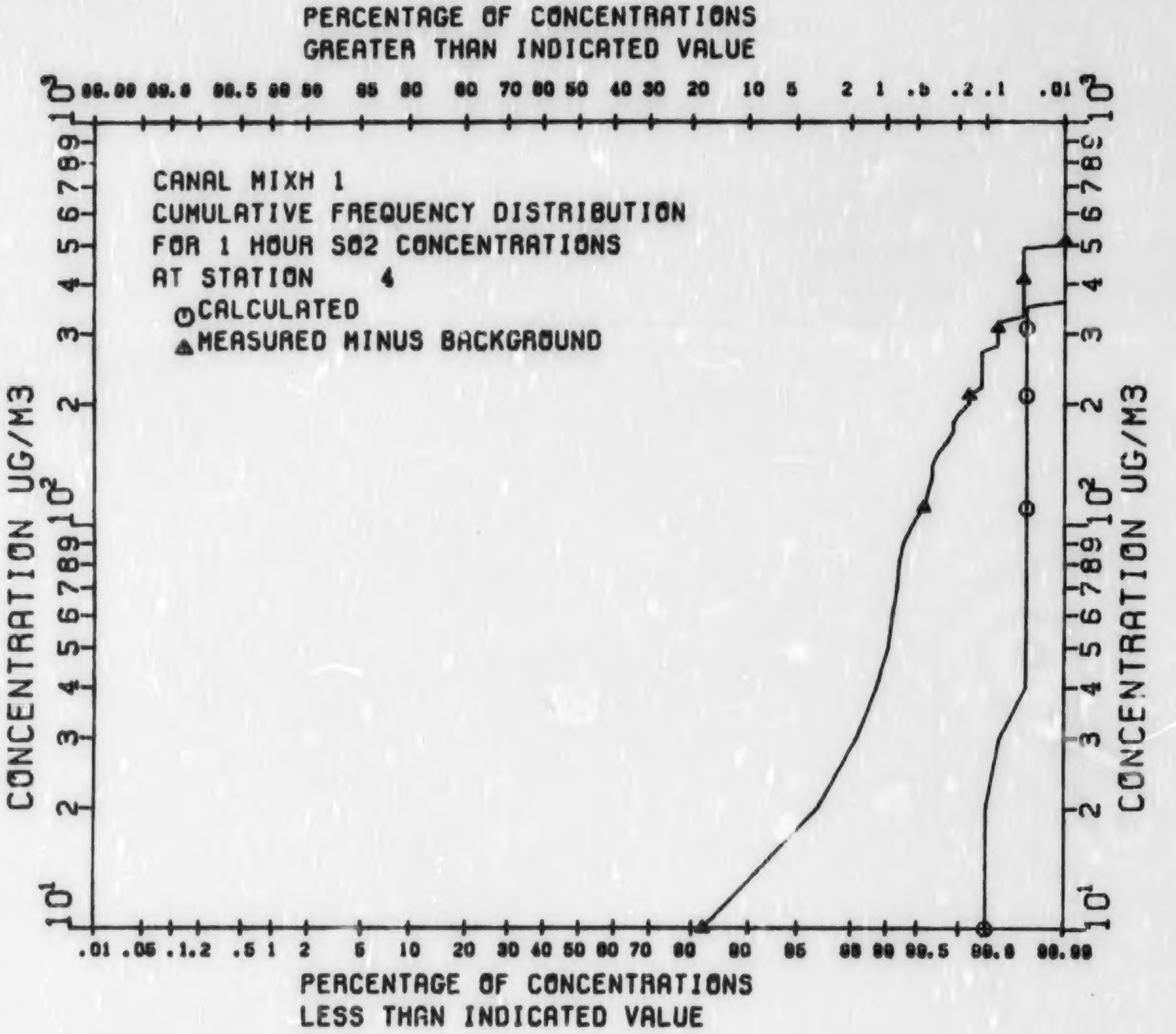

Figure A-25d. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 4 for mixing height class 1 (0 to 750 m)

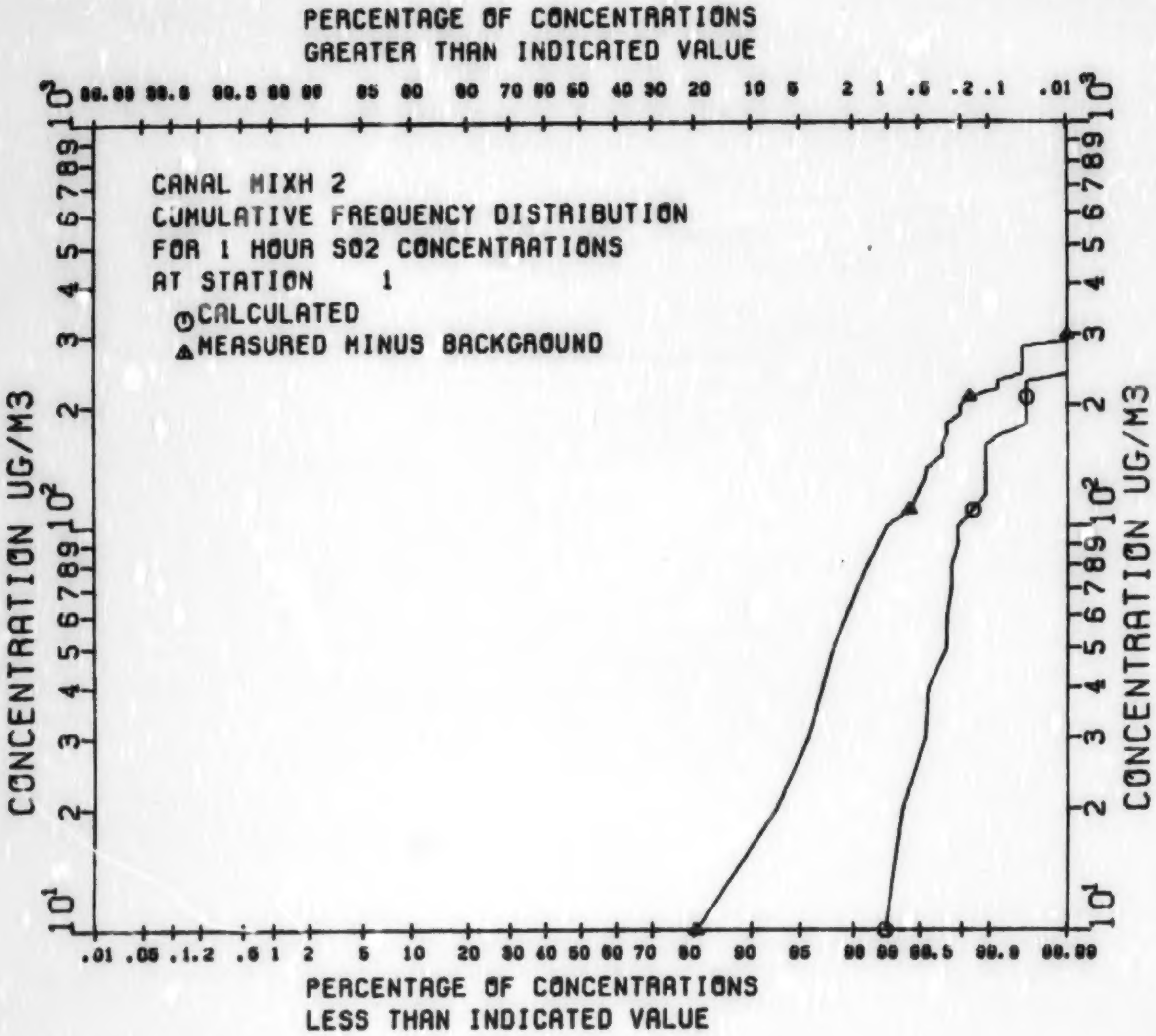

Figure 26a. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 1 for mixing height class 2 (750 to 1250 m)

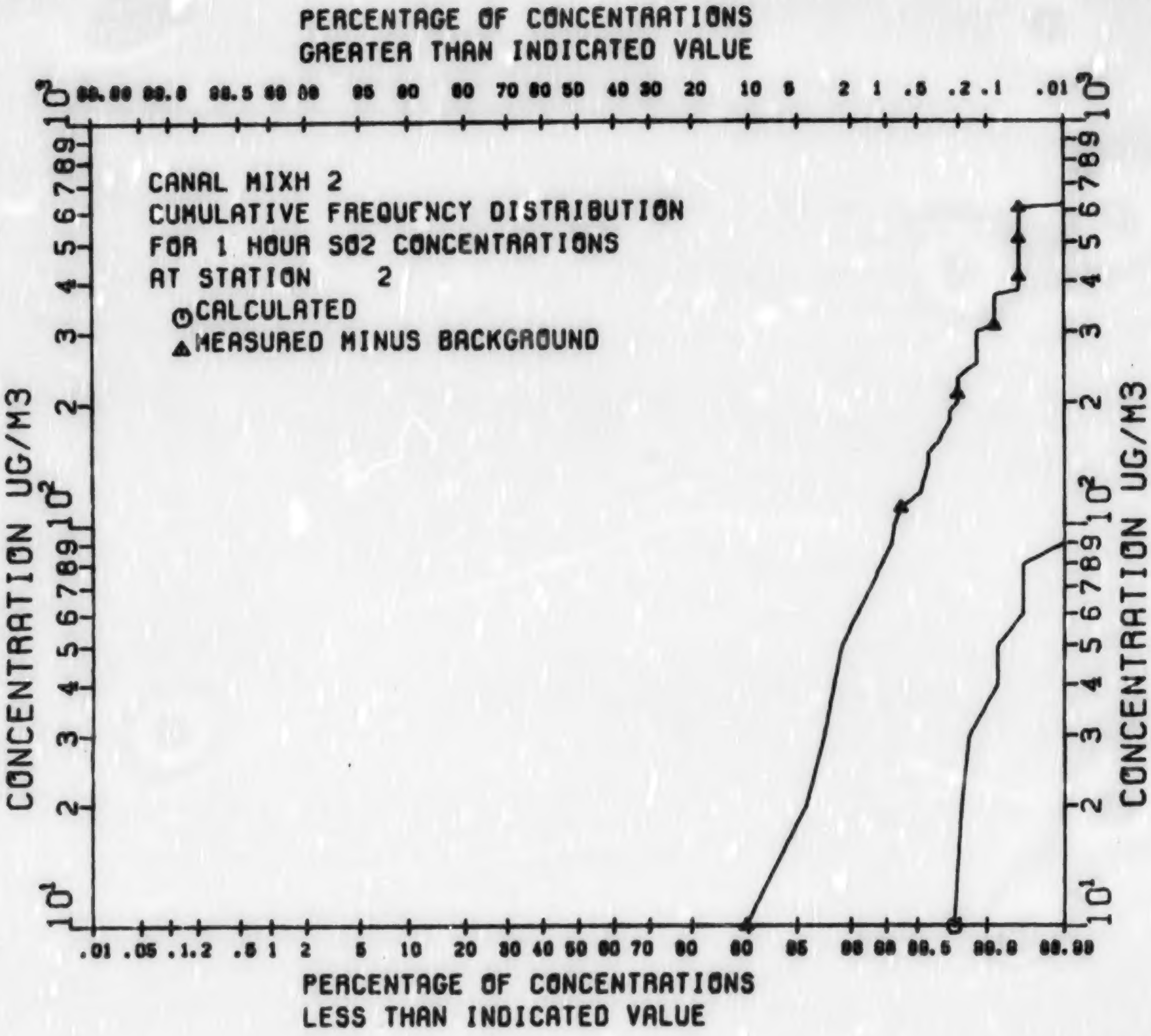

Figure A-26b. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 2 for mixing height class 2 (750 to 1250 m)

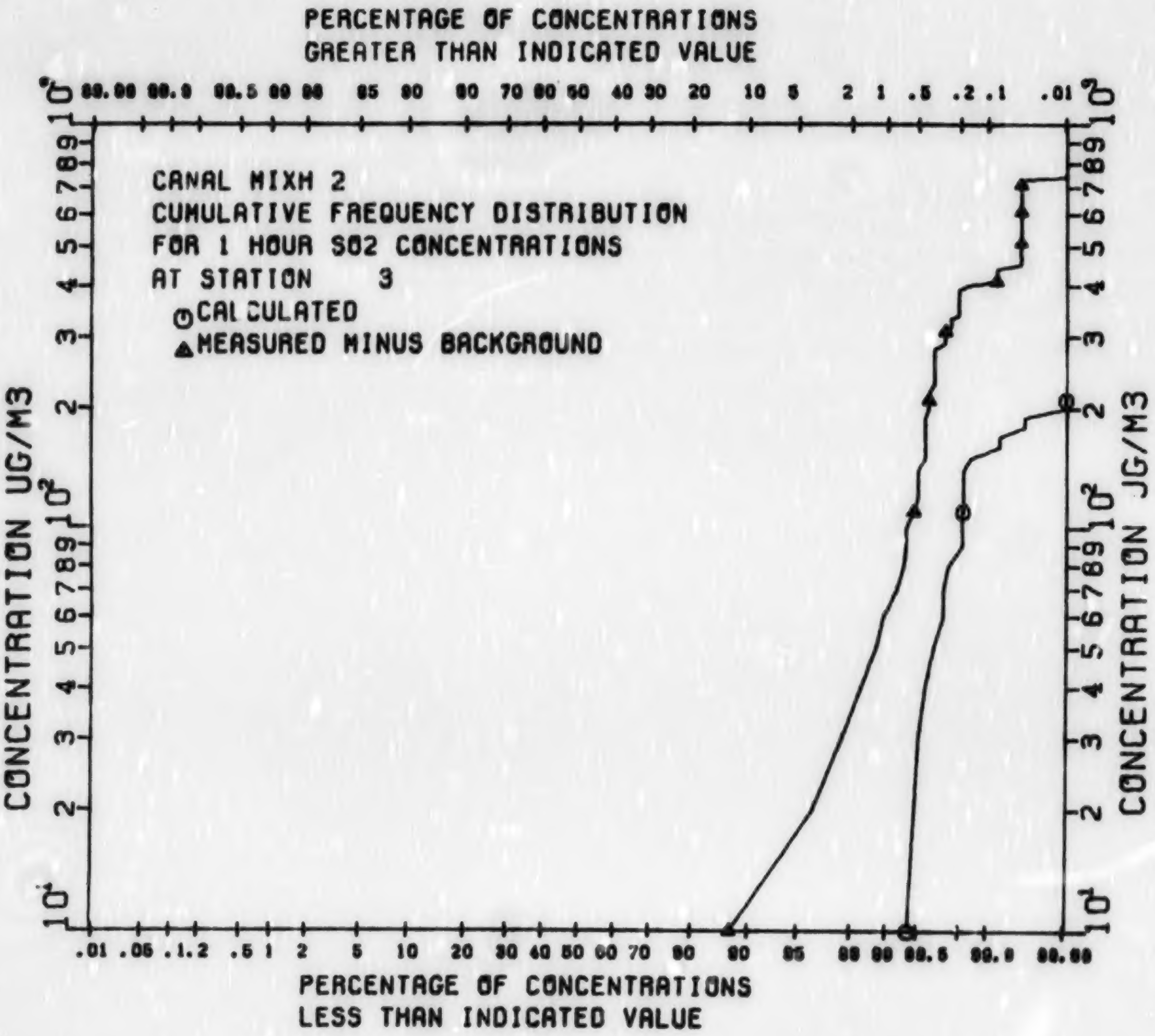

Figure A-26c. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 3 for mixing height class 2 (750 to 1250 m)

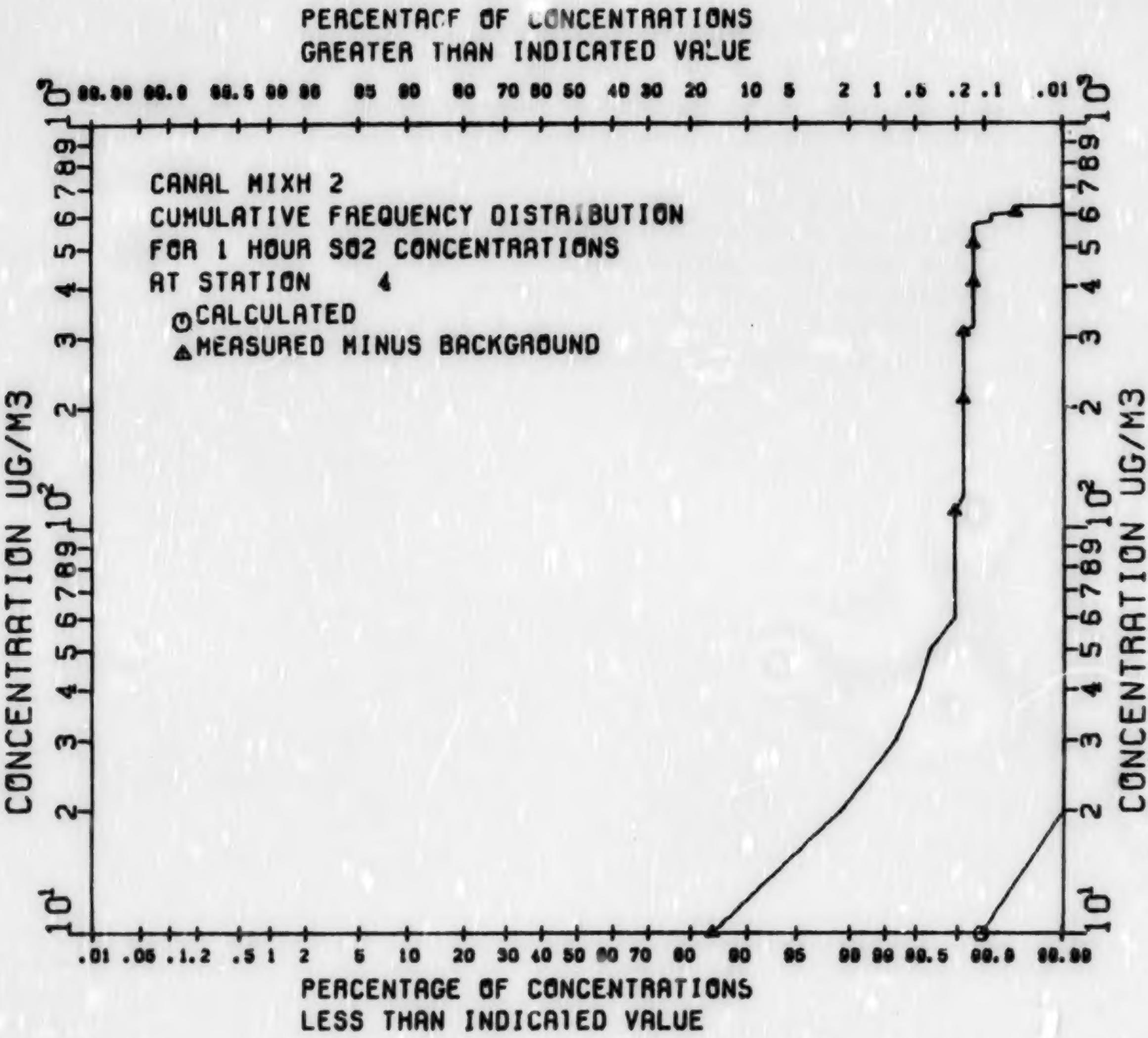

Figure A-26d. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 4 for mixing height class 2 (750 to 1250 m)

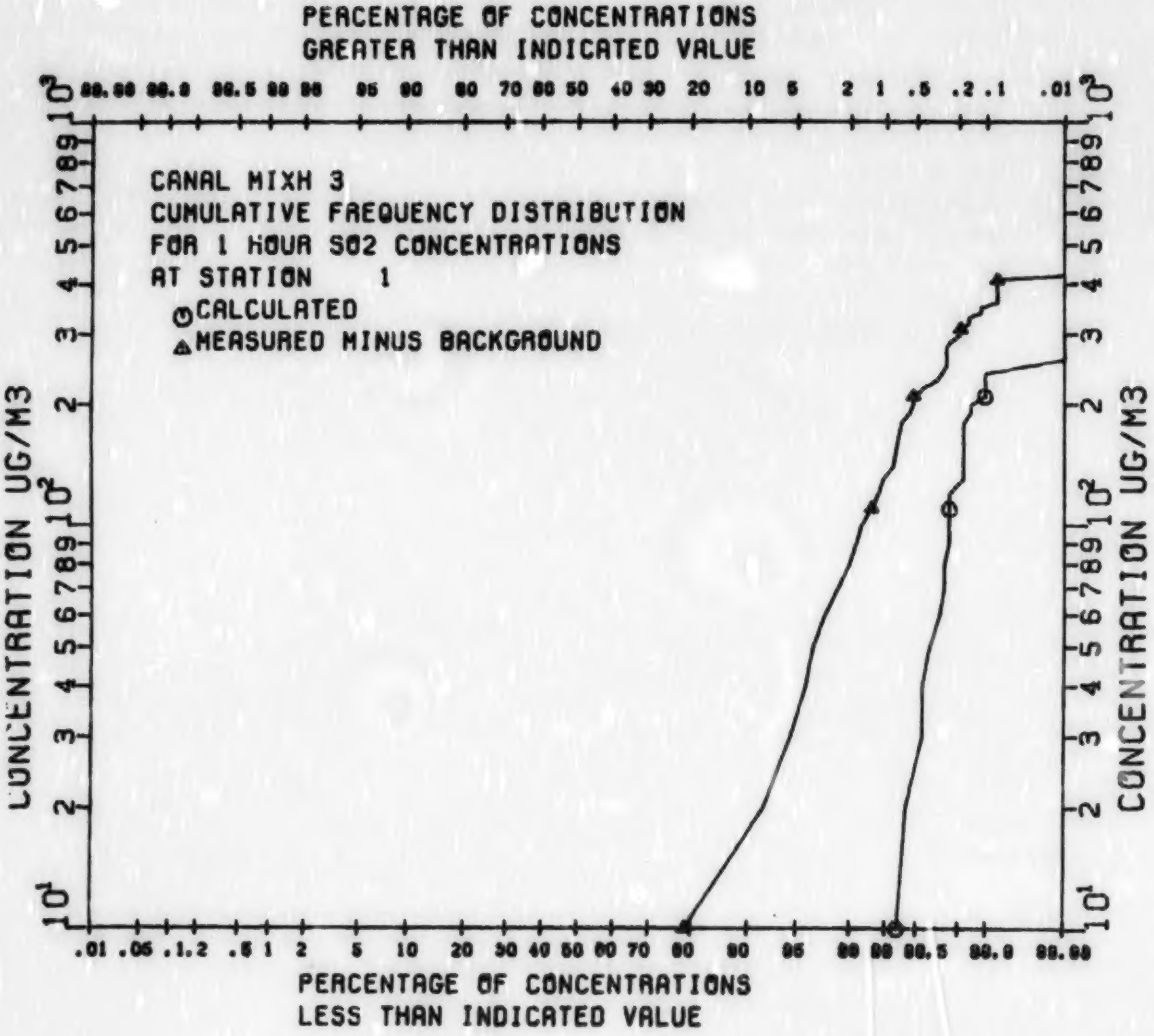

Figure A-27a. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 1 for mixing height class 3 (1250 m →)

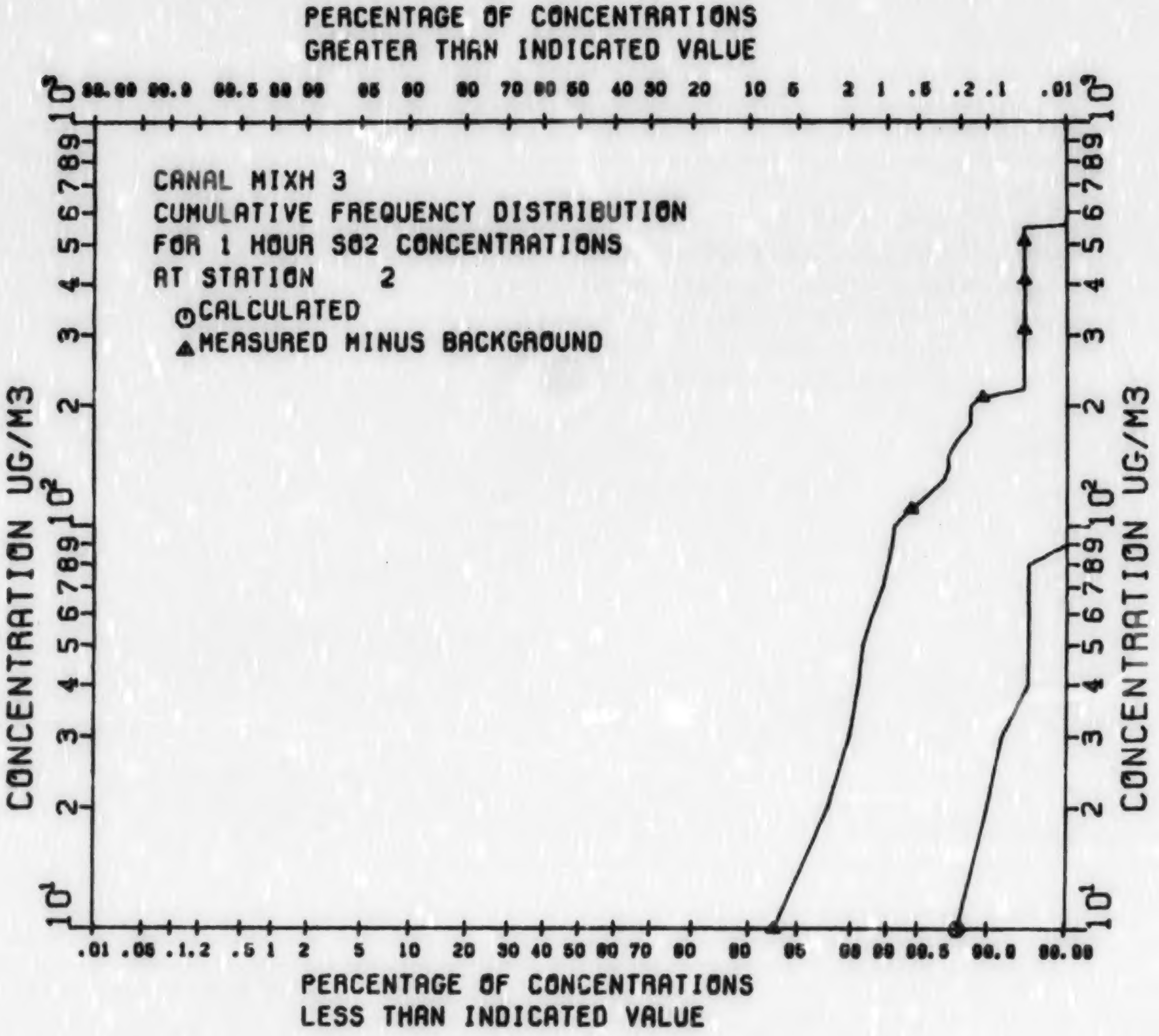

Figure A-27b. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 2 for mixing height class 3 (1250 m →)

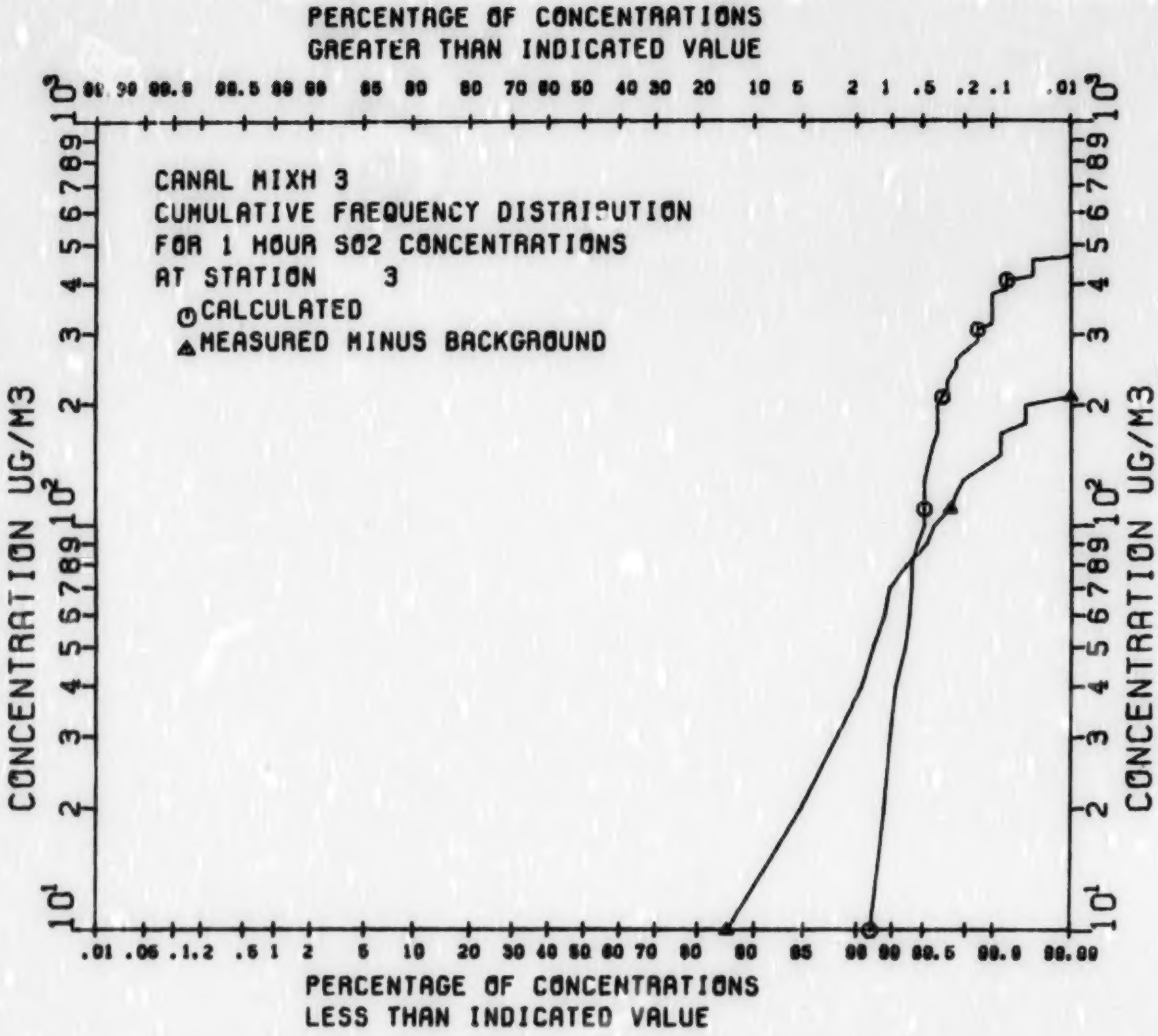

Figure A-27c. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 3 for mixing height class 3 (1250 m →)

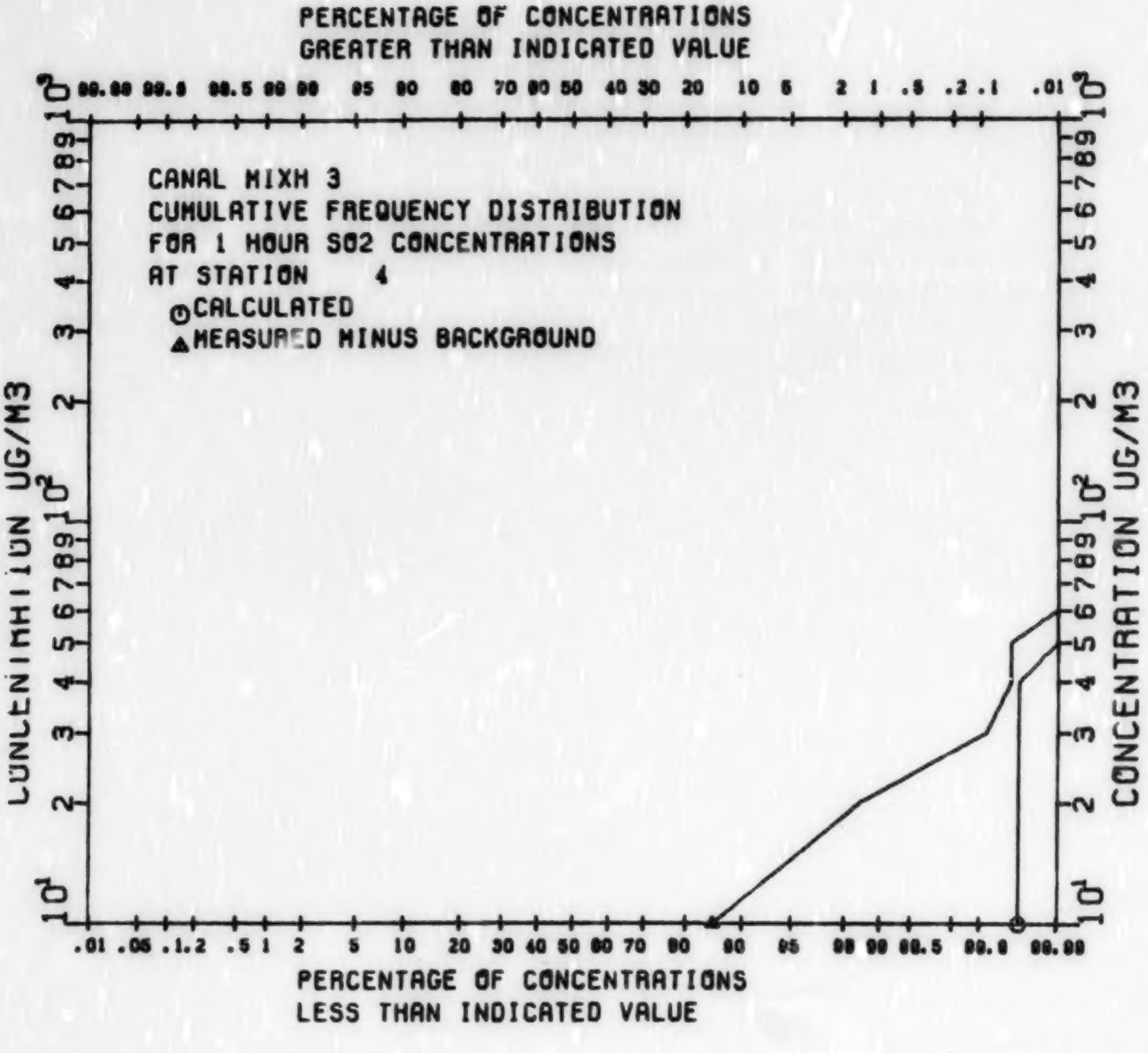

Figure A-27d. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Canal Plant for receptor 4 for mixing height class 3 (1250 m →)

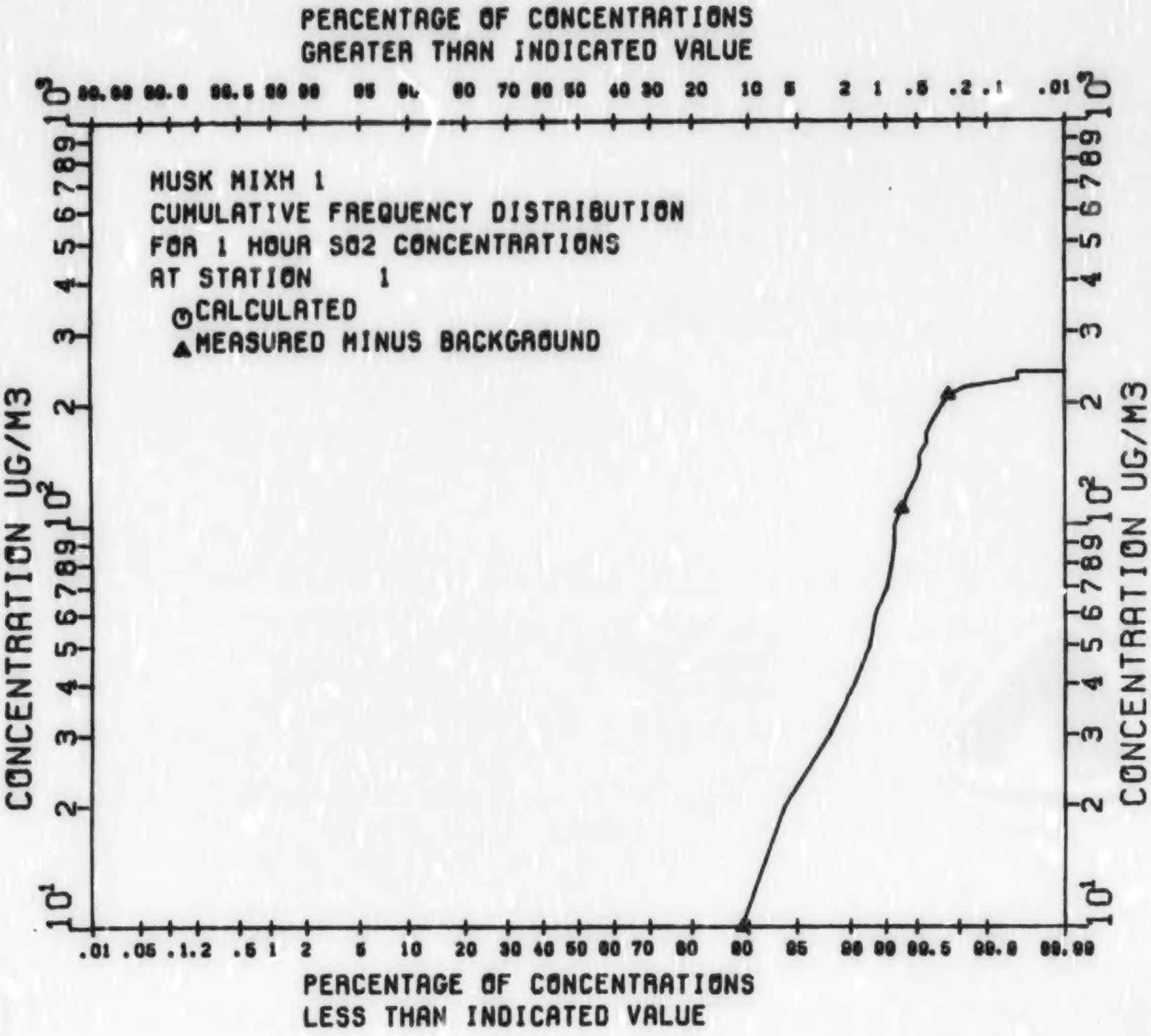

Figure A-28a. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 1 for mixing height class 1 (0 to 800 m)

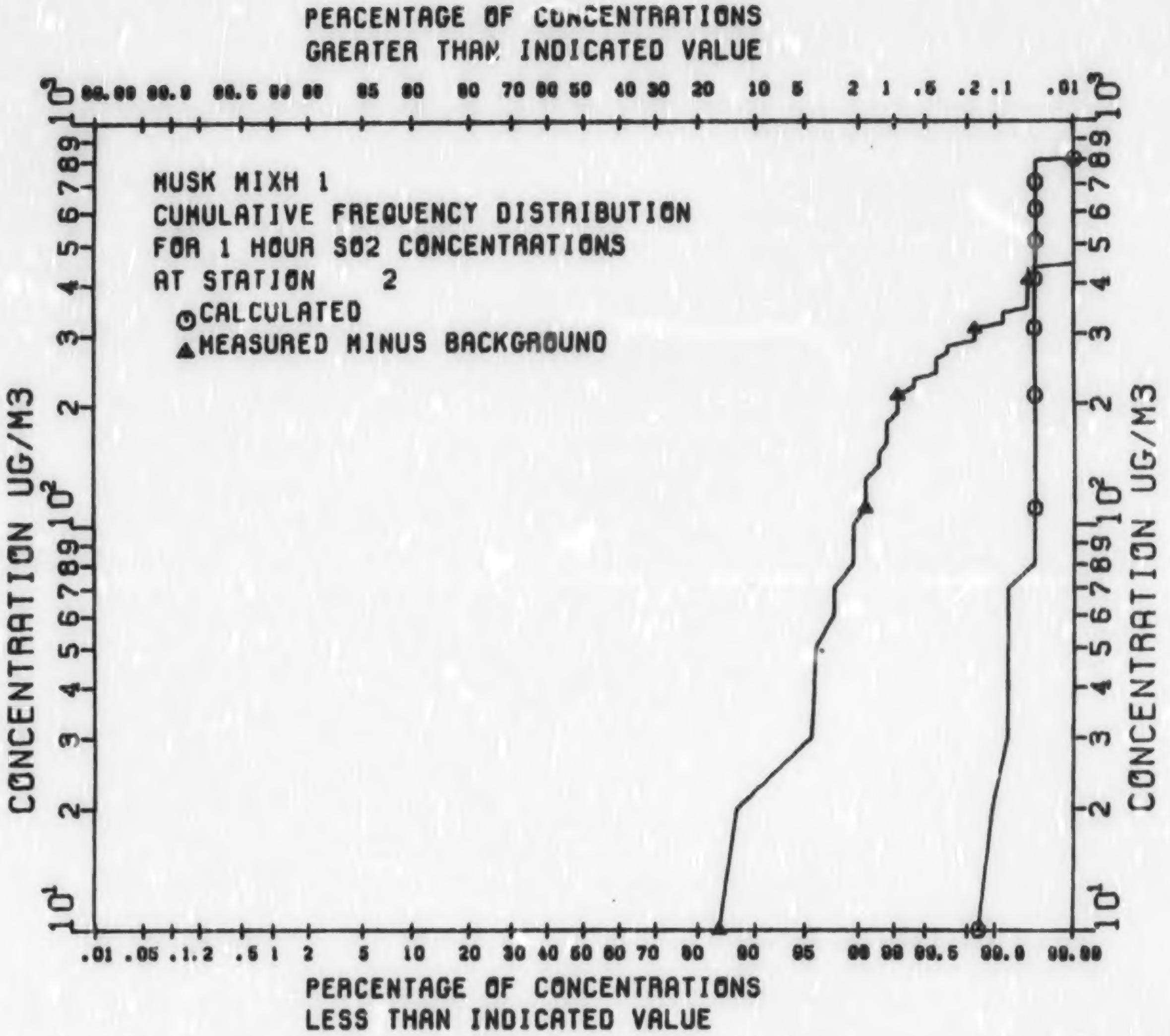

Figure A-28b. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 2 for mixing height class 1 (0 to 800 m)

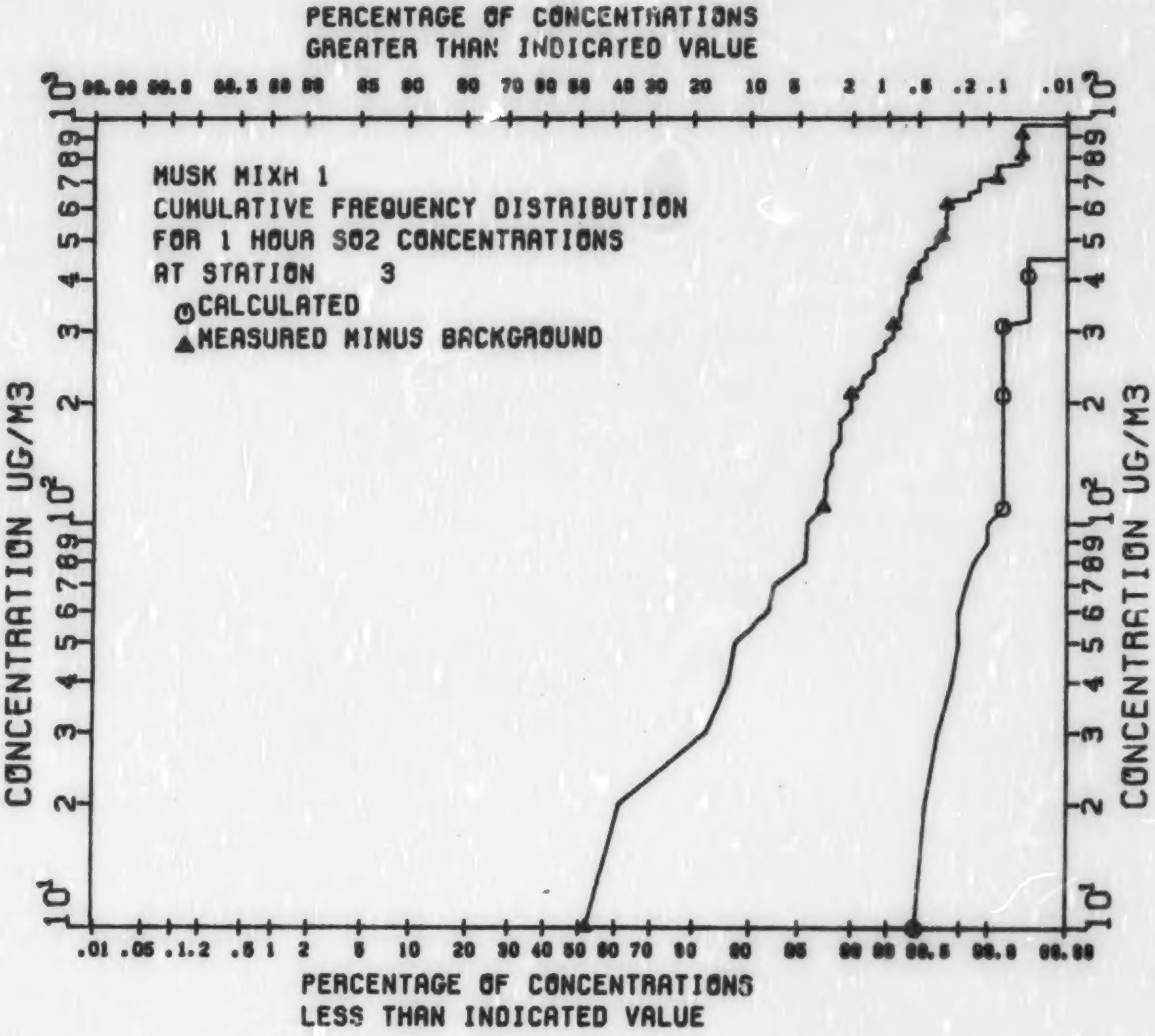

Figure A-28c. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 3 for mixing height class 1 (0 to 800 m)

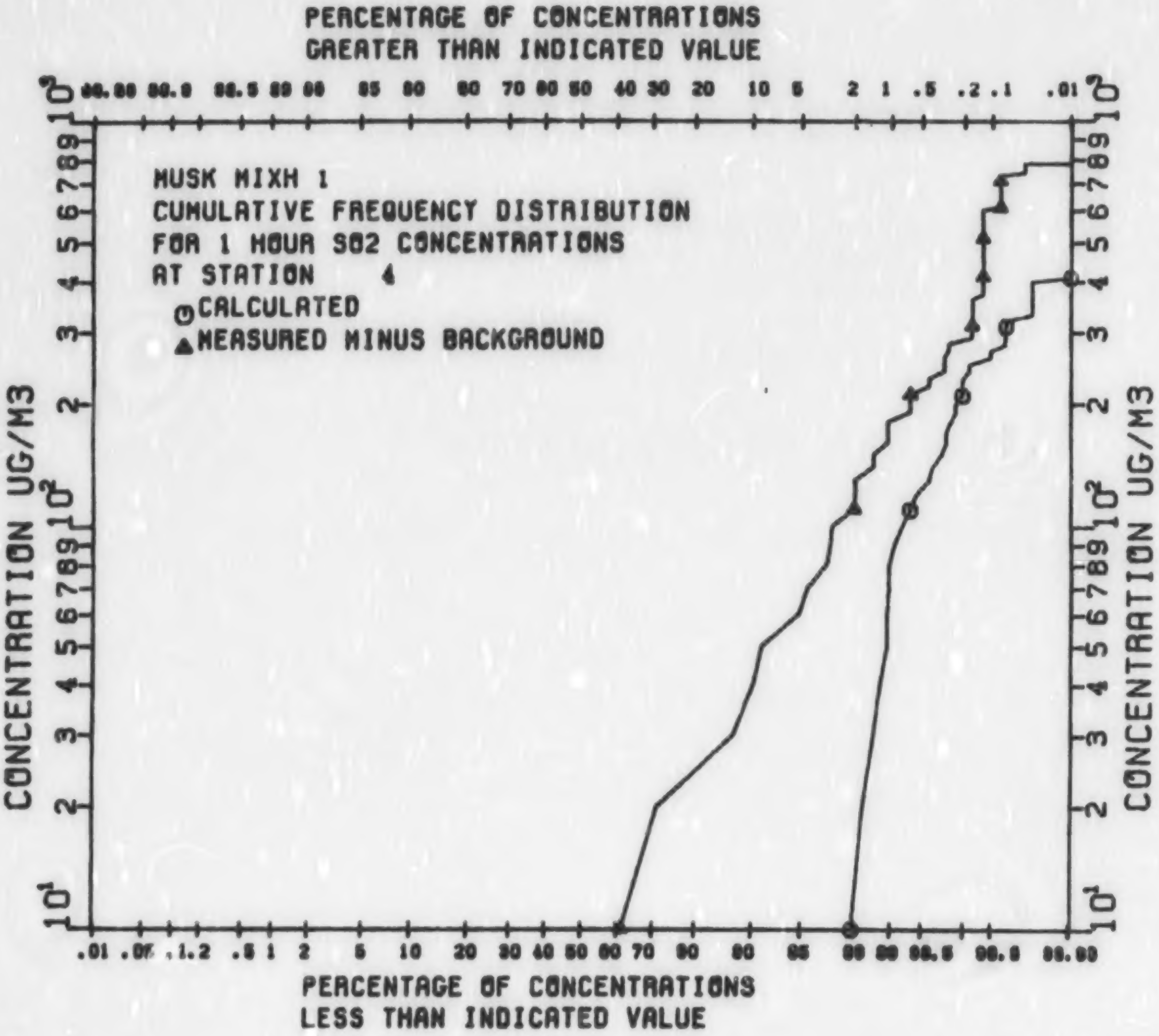

Figure A-28d. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 4 for mixing height class 1 (0 to 800 m)

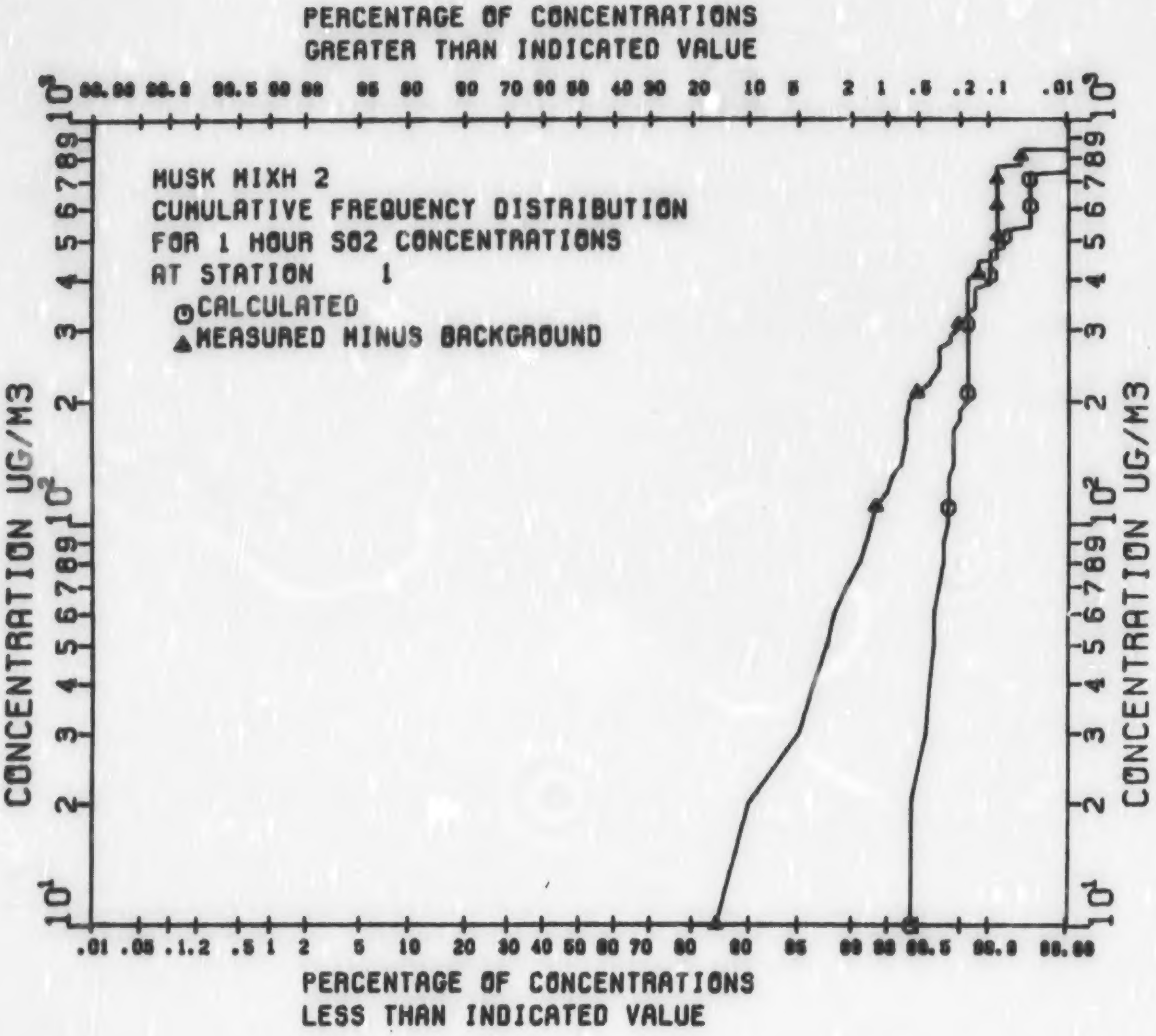

Figure A-29a. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 1 for mixing height class 2 (800 to 1200 m)

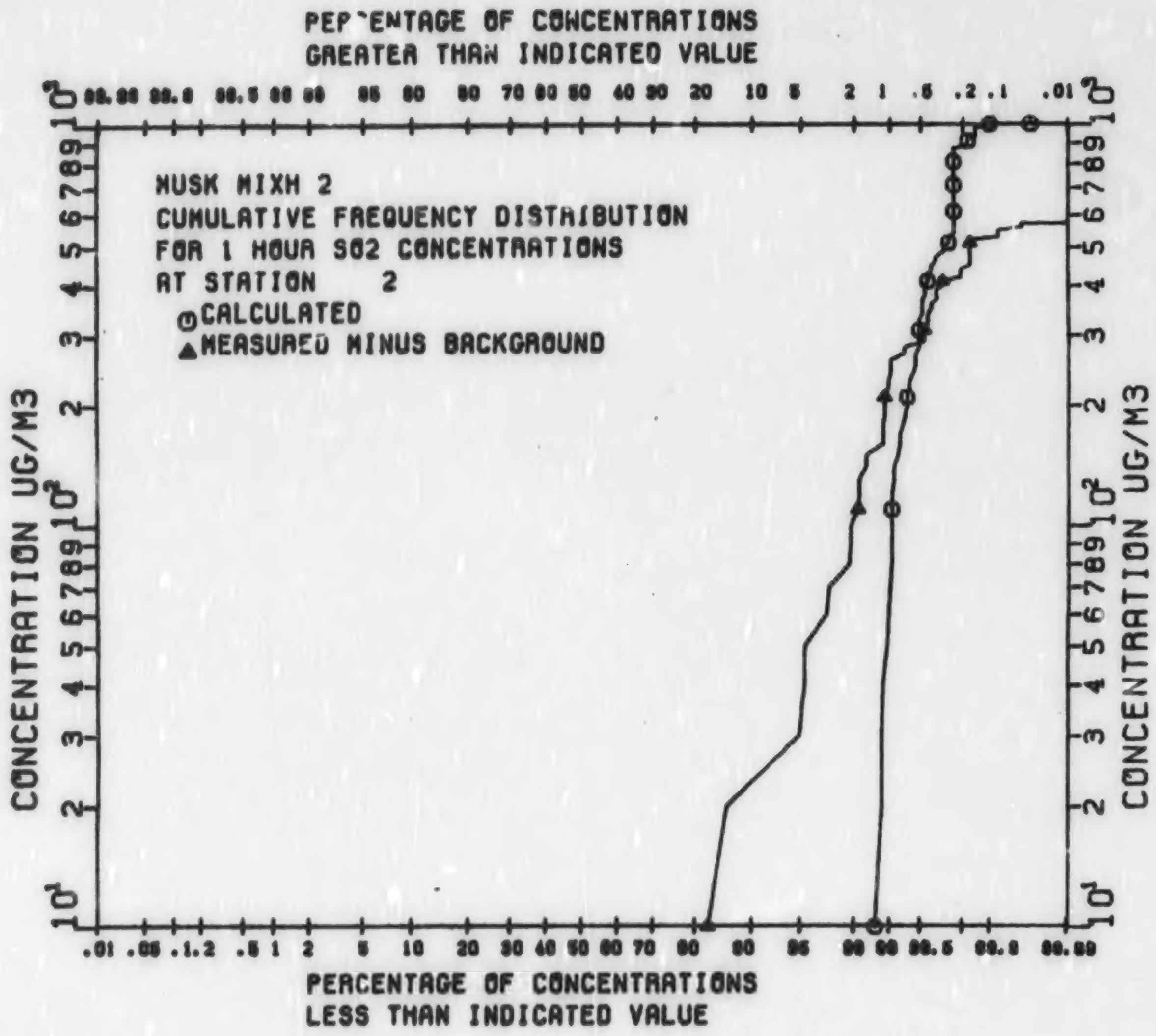

Figure A-29b. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 2 for mixing height class 2 (800 to 1200 m)

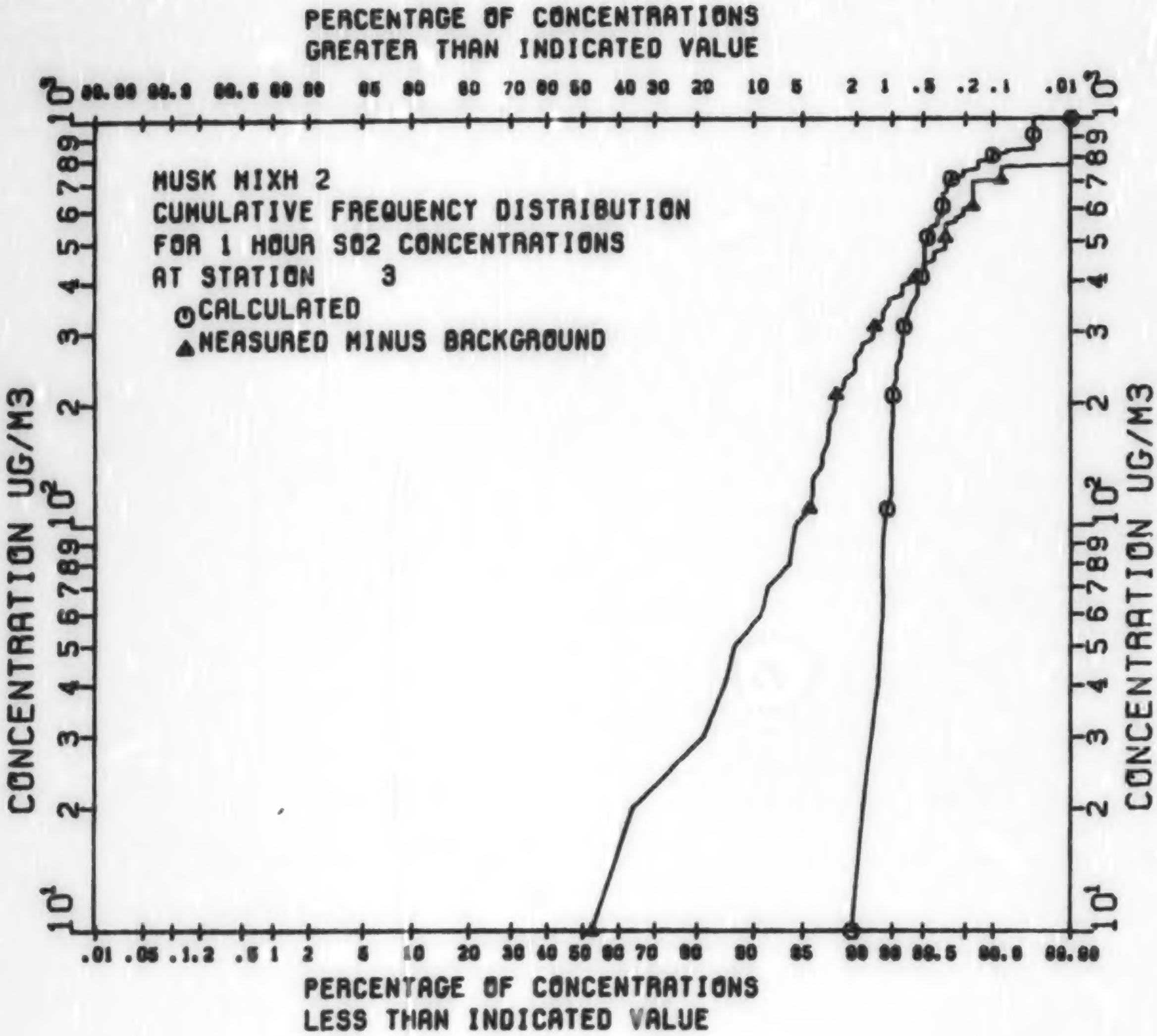

Figure A-29c. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 3 for mixing height class 2 (800 to 1200 m)

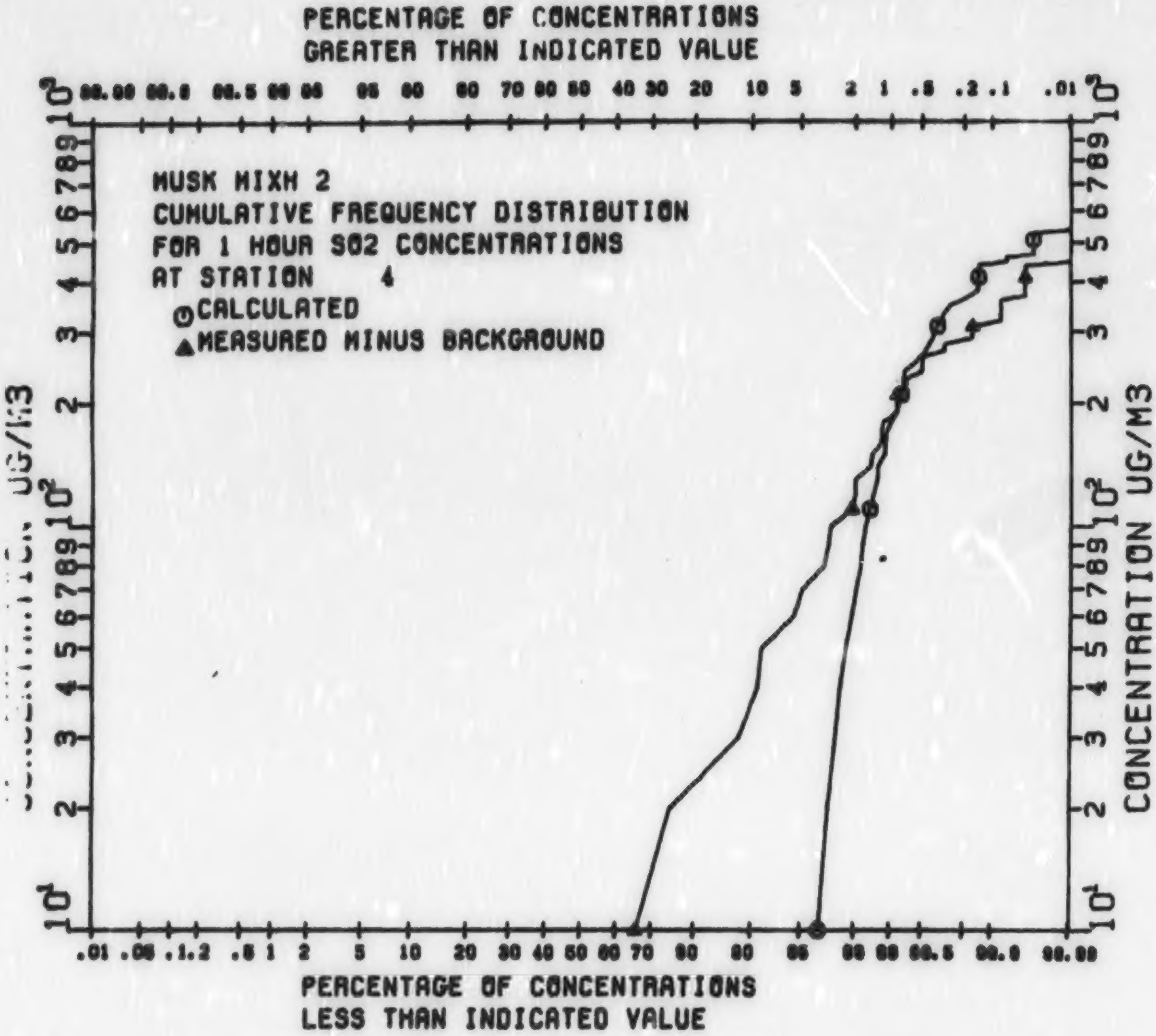

Figure A-29d. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 4 for mixing height class 2 (800 to 1200 m)

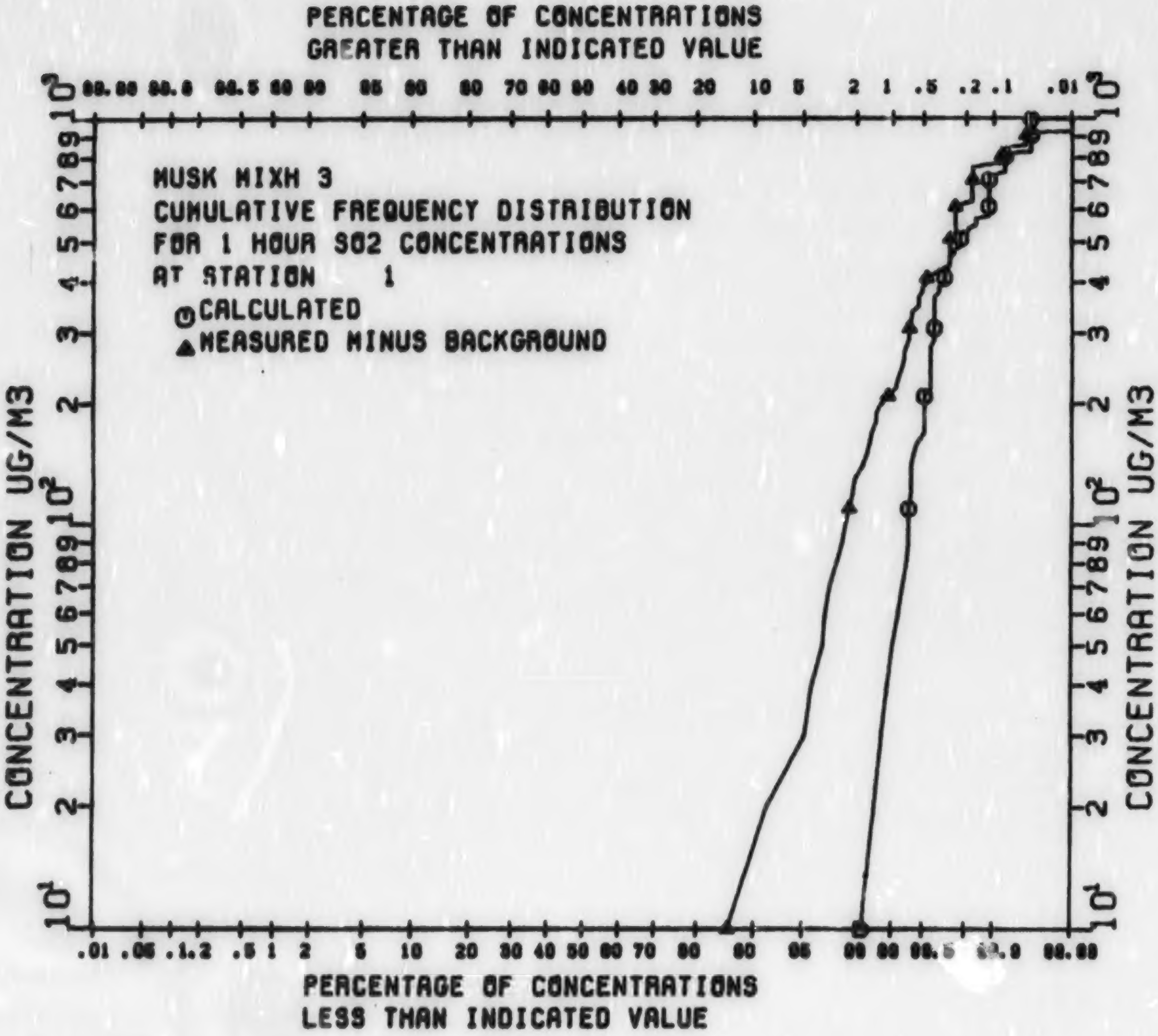

Figure A-30a. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 1 for mixing height class 3 (1200 m →)

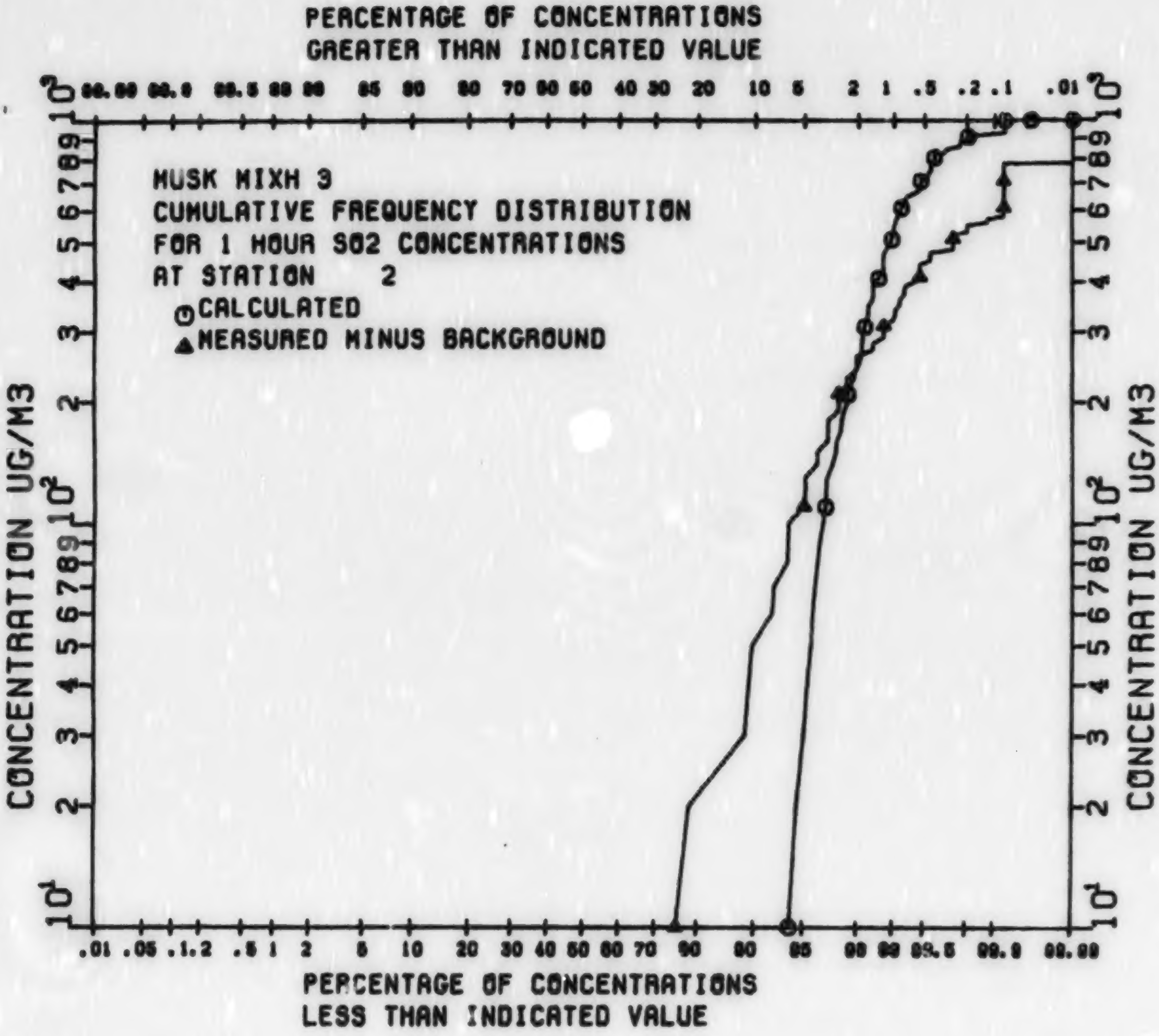

Figure A-30b. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 2 for mixing height class 3 (1200 m →)

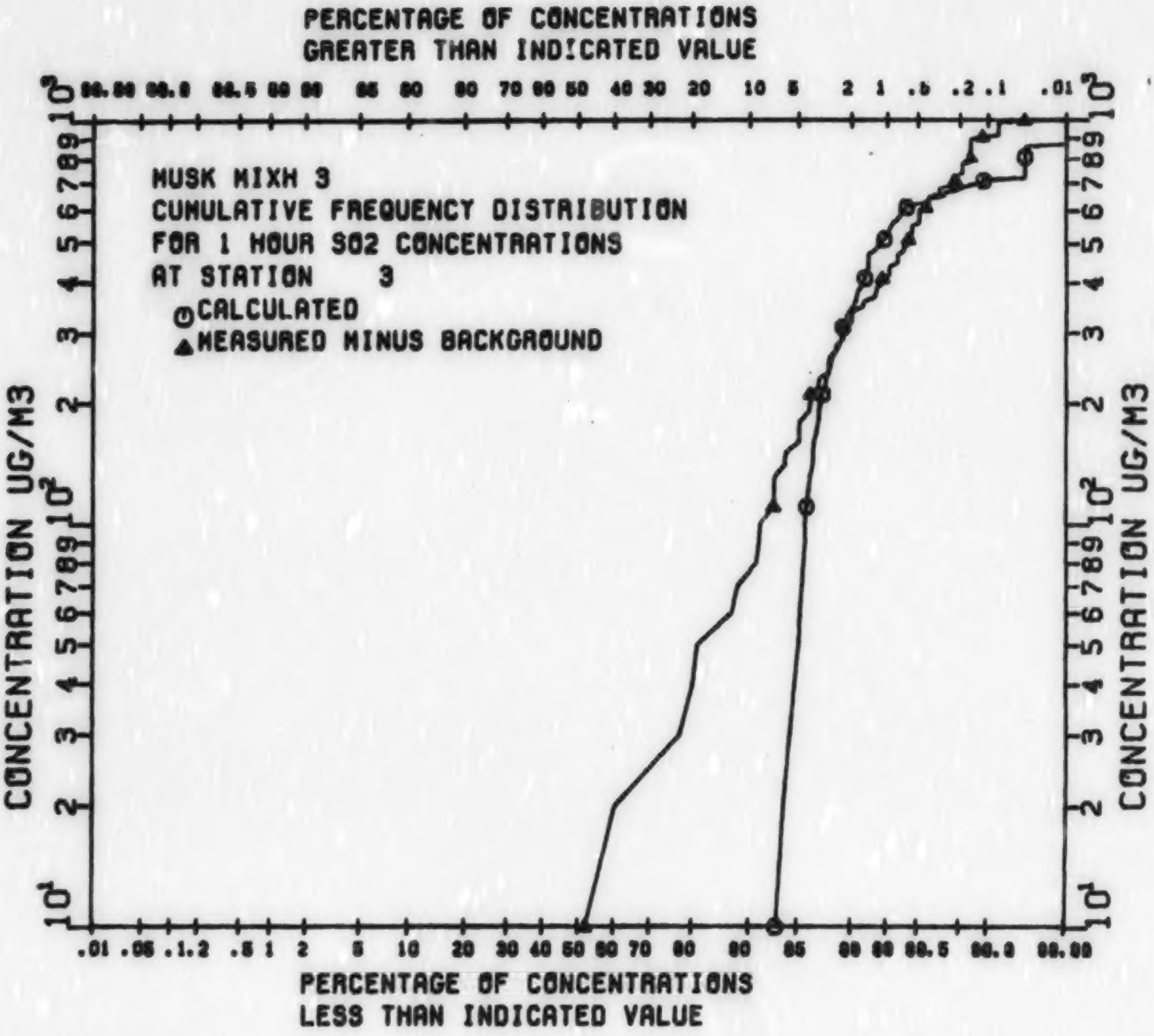

Figure A-30c. Cumulative frequency distribution of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 3 for mixing height class 3 (1200 m →)

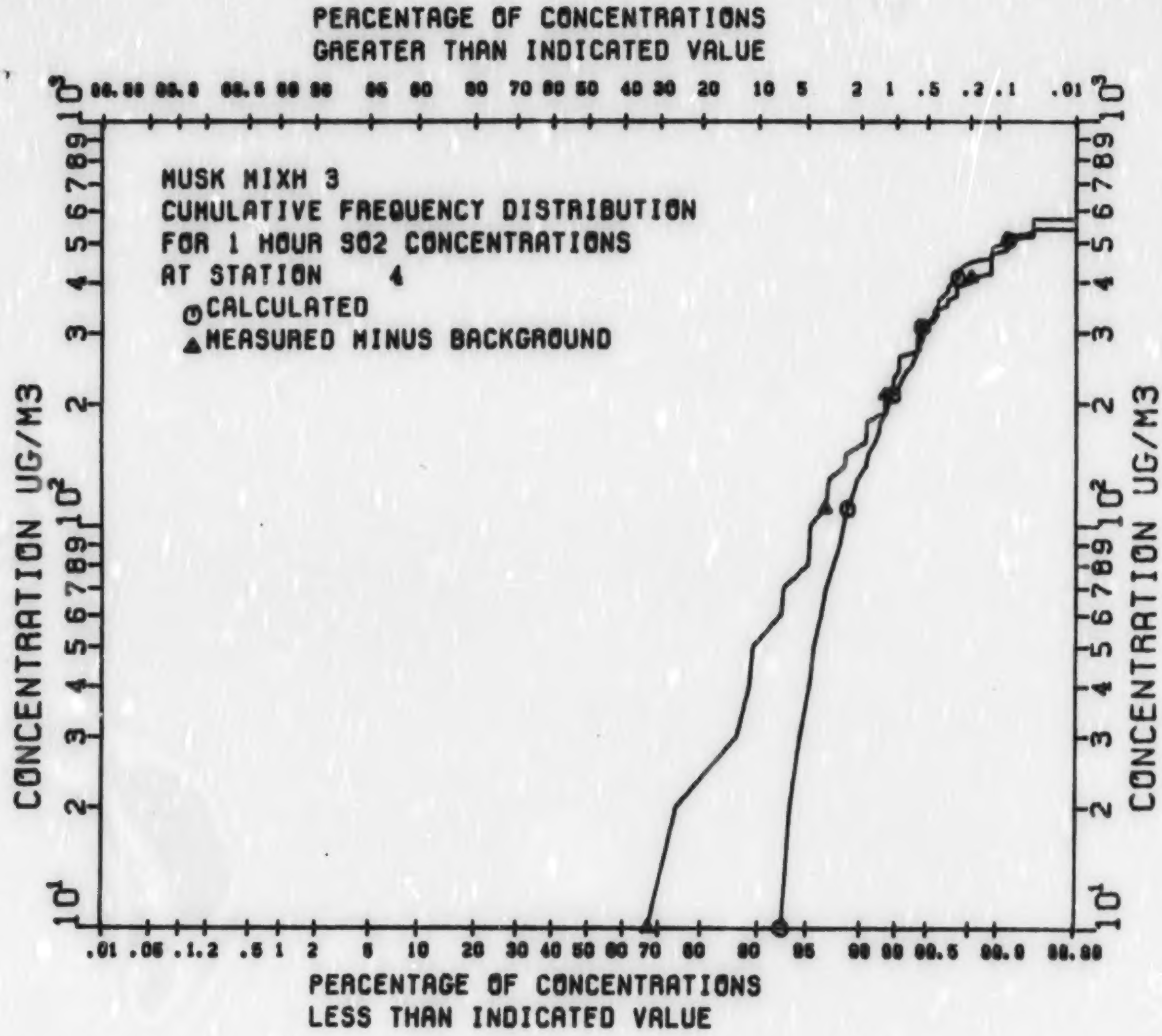

Figure A-30d. Cumulative frequency distributions of calculated concentrations and measured concentrations corrected for background at the Muskingum Plant for receptor 4 for mixing height class 3 (1200 m →)